ENGINEERING SCIENCE

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VOLUME II

HEAT AND HEAT ENGINES AND ELECTROTECHNICS

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PREFACE

THE two volumes which form *Engineering Science* have been planned to cover the full study of this subject in the Junior Technical School, and at the same time to present the work in the more intensive form required by evening students taking the first and second year National Certificate Courses who have to dispense with some of the practical and graphical work.

More precisely, its scope is that of the Engineering Science Course of the Junior Technical School, the first and second years of the Ordinary National Certificate Courses in Mechanical Engineering, the Engineering Science of the Ordinary National Certificate in Electrical Engineering, and the introductory work for the Institutions of Mechanical and Electrical Engineers examinations and those of the Scottish Education Authorities affiliated to the Royal Technical College, Glasgow. Volumes I and II will also be found to cover the subject-matter of many of the service and pre-service courses in engineering subjects and their application to engineering practice.

With very few exceptions, the approach to the subject is through detailed experimental work of either a demonstrative or individual character, and every effort has been made to bring the theory and examples into alignment with practice. The experimental work has been fully treated in the early chapters of the book, but as the student reacts to experimental methods less attention is given to detail and more is required of the student conducting the experiment. The verification and applications of principles have been the primary aim throughout the book, and exercises and examples have been chosen to give a practical bias, and to form the student's equipment for a more advanced study of the subject with the design of machines and structures.

The presentation has been made with a full appreciation of the lack of mathematical training in the early stages, and it is confidently recommended that a student should commence his study at

the same time as he approaches algebraic processes. Providing the mathematical knowledge grows in parallel stages with the study of this subject, there should be no period at which the science is obscured by the complexity of the mathematical processes employed.

Graphical solutions have been adopted, generally, as an alternative to mathematical solutions, and the appreciation and treatment of vectors has been introduced at a very early stage. A chapter has been devoted to the testing of materials, and although this is, of necessity, brief, it will probably cover the immediate requirements of students at this stage of their work.

It has been found that the amount of work to be covered could not be treated in a single volume of reasonable proportions, and, after consideration of the requirements of the courses for which this book is intended to cater, a division has been made on the following lines. Vol. I to include the whole of the Mechanics and Hydraulics required in the course, and Vol. II the Heat, Heat Engines and Electro-technics. Where these sections of the subject generally classed as Engineering Science are taken as a composite course, it is believed that the work is so arranged that the two volumes can be used in conjunction without detriment to the presentation.

In the Heat, Heat Engines and Electro-technics section, the main principles have been summarized so far as possible, and the work treated mainly along descriptive lines to prepare the student for the more detailed and quantitative treatment demanded by the later study in the National Certificate Courses.

The authors have found that many students enrolling for National Certificate Courses have received, in Junior Technical, Secondary or Central Schools, instruction in the elementary physics leading up to the work in Heat Engines and Electro-technics. Some elementary experiments have, however, been added as a supplementary scheme to illustrate certain fundamental physical principles and to cater for students who would profit by their performance of these experiments.

In the majority of Junior Technical Schools the Engineering Science is reinforced by a course of General Science, so that where the

book is employed for Junior Technical Schools this supplementary scheme of experiments need only be taken at the discretion of the teacher.

It is hoped that this book will provide a progressive course along practical lines, and will find its place among books suitable to the work for which it is planned.

The thanks of the authors are due to the firms who have been good enough to loan blocks and supply data concerning their manufactures. Among these may be quoted Messrs Cussons Ltd., of Manchester ; Messrs Morris Ltd., of Loughborough ; Messrs A. Macklow Smith, of Westminster , Messrs Babcock and Wilcox Ltd. ; Messrs C. A. Parsons Ltd., of Newcastle-on-Tyne ; Messrs Petters Ltd., of Loughborough, late of Yeovil ; The Zenith Carburettor Co. Ltd., of Stanmore ; Messrs Dobbie McInnes Ltd., of Glasgow ; The National Gas and Oil Engine Co. Ltd., of Ashton-under-Lyne ; Messrs Hopkinson Ltd., of Huddersfield ; Messrs Dewrance & Co., of London ; Messrs Hick, Hargreaves & Co., of Bolton ; The Premier Gas Engine Co. Ltd., of Nottingham ; The Standard Motor Co. Ltd., of Coventry ; Messrs Philip Harris Ltd., of Birmingham ; and Messrs Skefco Ltd., of Luton.

Particular appreciation is due to Sir Richard Gregory, who has ungrudgingly lent his wide experience to the effective production of the book, and many suggestions of his have been adopted with very happy results.

Grateful acknowledgement is also gladly made to Mr. A. J. V. Gale, M.A., and Mr. F. G. W. Brown, M.Sc., for kindly reading through the proofs and making many helpful and valuable suggestions. The authors also wish to thank the publishers and authors concerned for permission to include tables of logarithms and diagrams from their publications, especially from Castle's *Practical Mathematics for Beginners*. Duncan and Starling's *Text-Book of Physics*, Duncan's *Steam and Other Engines*, and Gregory and Hadley's *Class-Book of Physics*.

Permission has been kindly given by Messrs Edward Arnold & Co. to include data from their *Callendar's Abridged Steam Tables*, and acknowledgement is gladly accorded to the following authorities for

permission to include a selection of their examination questions: The Union of Lancashire and Cheshire Institutes; The Union of Educational Institutions; The Institutions of Mechanical and Electrical Engineers; The Scottish Educational Authorities affiliated with the Royal Technical College, Glasgow.

The authors would be very glad to receive, from teachers and others, notification of any errors which may have escaped detection.

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February, 1937

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CHAPTER I

ENERGY VALUE OF FUEL AND ITS MEASUREMENT—COMBUSTION — EFFECTS OF HEAT — MEASUREMENT OF TEMPERATURE AND PRESSURE — HEAT AND ITS MEASUREMENT—CONVERSION OF ENERGY

Fuel is the term applied to solid, liquid or gaseous materials used to create heat energy by burning in air or oxygen. When fuel is ignited and placed so that a stream of air can pass through and over it, a chemical action takes place with the production of a large amount of heat and sometimes light and sound energy. The chemical energy of the fuel is mainly transformed into heat energy. Coal is by far the most important fuel in the world, and the many varieties have been produced in the course of ages by the action of decay, heat and terrific pressure upon stratified accumulations of vegetable and woody material. A brief description of the most important fuels will be found on p. 52. The bulk of the natural fuels such as coal, wood, oil and natural gas consist of compounds of carbon, hydrogen and oxygen, together with small proportions of nitrogen, sulphur, moisture and mineral ash. Of these only carbon, hydrogen and sulphur will burn in air. The oxygen in the fuel supplies only a portion of that required for burning, and the chief source of supply of oxygen for combustion is the air. The burning of a small portion of fuel, which has been ignited, will generate sufficient heat to maintain combustion.

All matter, including fuels, can be divided into elements, mixtures and chemical compounds. An **element** is a substance, such as carbon, which has never been divided into two or more chemically different constituents. A **chemical compound** consists of elements which have combined in definite proportions characteristic of it, and which are held together by a chemical attraction or force. Water is a compound, and it differs entirely from its constituent elements, namely hydrogen and oxygen. A compound requires a chemical action,

caused by heat or electrical energy, to split it into its elements, and the process of splitting involves no loss or gain of weight. A **mixture** possesses the properties of its constituents, between which no chemical action has taken place. Air is a mixture, mainly of nitrogen and oxygen, and contains about 23% of the latter by weight.

Oxidation. This is the process of formation of a chemical compound between an element and oxygen. Rust or iron oxide is produced by slow oxidation of the iron, while rapid oxidation occurs in the burning of the carbon and hydrogen compounds at a gas jet. Carbon combines with the oxygen of the air to form carbon dioxide, and hydrogen combines with oxygen to form steam or water. If carbon is burnt in an insufficient supply of oxygen, carbon monoxide gas is formed, and only about $\frac{3}{10}$ths of the heat available is developed. Carbon monoxide will itself burn to carbon dioxide in air or oxygen and develop the remaining $\frac{7}{10}$ths of the heat to be derived from complete combustion to carbon dioxide. Sulphur burns to form sulphur dioxide gas, and in special circumstances phosphorus, magnesium and aluminium can be used as fuels.

EXPT. 1. **Oxidation.**

OBJECTS. *To find the increase of weight of a piece of iron due to oxidation.*

METHOD OF PROCEDURE. Polish, with emery cloth, a length of about 24 inches of iron wire of heavy gauge. Wind this wire into a coil, closely wound, and about 1 inch diameter. Carefully weigh the coil, and subject it to heat from a series of burners in order to produce red heat, but not white heat. After a time the iron will become blackened ; if it is heated too fiercely it will burn, but providing the heat is regulated a coating of oxide will develop on the iron. Weigh the iron after heating and account for the difference in weight produced by the heat.

CONCLUSIONS. The process of heating polished iron in air produces an oxide of iron at the surface. Since the oxide is formed by combination of the iron with the oxygen of the air, the coil after heating will weigh more than before heating.

Combustion. Rapid oxidation is really a form of combustion. The latter may be defined as a chemical action or change between two substances accompanied by the production of heat, light and

sometimes sound energy. Flame, which usually accompanies combustion, marks the surface of contact between a combustible such as hydrogen and a supporter of combustion such as oxygen or air. The rapid oxidation produces such high temperatures that the small particles of the new compounds formed become radiant. The highest temperature to which a body can be raised without producing a flame is called the **point of ignition.** For coal it is about 660° F. In the case of oil fuels the temperature of ignition is called the **flash point.** The flash point for oil ranges from about 430° F. to 800° F., and is naturally dependent on the type of oil. For gaseous fuels the ignition temperatures are still higher, and may be as much as 1560° F. **Spontaneous combustion** occurs when the heat of oxidation accumulates in badly ventilated places until the point of ignition is reached. The same total quantity of heat is generated for a given combustion, however long oxidation takes or short the time of combustion.

The combustion of coal is really a very complex process, and a full treatment cannot be given here. When heated, coal gives off gaseous products which, if the point of ignition is reached and sufficient oxygen is available, burn above the coal and leave the residual solid fuel to burn.

Since 1 lb. of carbon requires $2\frac{2}{3}$ lb. of oxygen to form $3\frac{2}{3}$ lb. of carbon dioxide, and 1 lb. of hydrogen requires 8 lb. of oxygen to form 9 lb. of steam, and 1 lb. of sulphur requires 1 lb. of oxygen to form 2 lb. of sulphur dioxide, it is possible to calculate the **least amount of air, or minimum air,** to burn completely a quantity of fuel, provided the chemical analysis of the fuel is known. (See p. 35.)

Example. *If* 1 *lb. of anthracite coal contains* 0·9 *lb. of carbon,* 0·025 *lb. of hydrogen and* 0·005 *lb. of sulphur, estimate the least quantity of air necessary to burn it.*

0·9 lb. of carbon requires $\frac{9}{10} \times \frac{8}{3} = 2{\cdot}4$ lb. of oxygen.
0·025 lb. of hydrogen requires $\frac{1}{40} \times 8 = 0{\cdot}2$ lb. of oxygen.
0·005 lb. of sulphur requires $\frac{1}{200} \times 1 = 0{\cdot}005$ lb. of oxygen.
Total $= 2{\cdot}605$ lb.

In 100 lb. of air there is 23 lb. of oxygen, therefore

$$\text{the amount of air required} = 2{\cdot}605 \times \frac{100}{23} = 11{\cdot}33 \text{ lb.}$$

Actually about 18 lb. of air per lb. of fuel would be the least practical allowance. That is 18 − 11·33 or 6·67 lb. of **excess air** is usually necessary. In the above approximations the oxygen content of the fuel itself has been ignored. If oxygen is present in the fuel the amount of it is deducted from the weight of oxygen in the air to be supplied.

Control of combustion in the boiler furnace and internal combustion engine. Rapid combustion, and the consequent great intensity of heat produced, is necessary for the greatest efficiency in the boiler furnace and in the internal combustion engine cylinder. The principles of efficient combustion can be dealt with for these two cases. The steam engine illustrates the external combustion engine where the fuel is burnt in a separate vessel called the boiler while the internal combustion engine has, as its name implies, a self-contained combustion chamber called the engine cylinder.

The boiler furnace. The function of a boiler is to employ the heat energy developed by combustion to generate steam economically. To achieve this the air and fuel supply must be so arranged that complete combustion occurs with the least amount of excess air and in the minimum of time. A chimney must always be provided to discharge the products of combustion well above ground level so as not to create a nuisance. The chimney also serves to create the necessary strong current of air or draught through or over the fuel. In the chimney the hot gases are less dense than the cold air outside, and the unequal density condition thus set up causes the hot gases to rise and leave the chimney. Colder fresh air is caused to enter through and above the fire, and keeps it burning. This **natural draught,** as it is called, can be made a maximum if:

(1) all the air is made to pass through the furnace, as leakage lowers the temperature of the furnace;
(2) an even thickness of fire is maintained and the thickness adjusted to the draught;
(3) the cold air admitted above the fire, to burn the volatile products given off when the fuel is freshly supplied, is reduced to a minimum.

Since a chimney is rather an expensive structure, fans are often used to increase the draught or air supply, and they are used if more

than 30 lb. of coal per sq. ft. of grate area per hour are to be consumed. **Forced draught** is obtained by fans or a steam blast delivering air under pressure to the furnace. **Induced draught** is obtained by placing fans at the base of the chimney and drawing air through the fire and flues, the whole of the gaseous products of combustion together with excess air passing through the fans into the chimney.

Attention will now be given to the arrangement of the fuel or to **stoking.** The ideal condition of a furnace is a uniform state of white incandescence, and this means that the fuel must be supplied in thin even layers at frequent intervals. At the same time a little extra air should be allowed to reach the fire above the fuel to burn the volatile products and lessen the smoke. This may also be accomplished by adopting **alternate side firing**, which involves firing the right hand side of the furnace at one time and the left hand side at the next. Another method is called **coking stoking**, in which fresh fuel is thrown on the front portion of the grate, and after being more or less coked, it is pushed bodily to the back or bridge end of the fire to make way for a new supply. This latter method is that adopted in the mechanical chain grate stoker (p. 134).

Pulverised or finely ground fuels and oil fuels are being increasingly used in boiler furnaces. No grate or stoker is needed and there is more space for combustion. Finely powdered coal dust or oil is sprayed under pressure into the combustion chambers, combined with forced or induced draught; this maintains rapid combustion and produces very high temperatures. To reduce maintenance costs, it is found necessary to water-cool the furnace lining, and this is becoming standard practice, especially in large installations. It is found that the presence of an incandescent surface of material which does not easily fuse causes the flameless and complete combustion suitable for raising steam. The temperature, although high, is more even, and there is less straining of the parts due to unequal expansion. Also the large amount of radiant energy released ensures rapid transmission to the water. This principle of surface combustion has been applied to the burning of gaseous fuels in boilers, cookers and heaters, slight pressure being used to force a mixture of air and gas through porous non-fusible material, so that the gas burns on the

outside surface, which becomes incandescent as the result of this combustion.

The internal combustion engine. If a combustible, such as hydrogen or petrol, be intimately mixed with air or oxygen, in suitable proportions, the mixture becomes explosive ; that is, combustion can take place with extreme rapidity. Should the mixture be confined and then ignited, as in an engine cylinder, the heat suddenly developed raises the temperature, and consequently the pressure, very quickly. It is this explosion pressure which is the source of power in gas and petrol engines. To make an explosive mixture, the percentage of combustible present must lie between certain limits. The rapidity of the combustion depends upon (1) the shape of the combustion chamber, (2) the properties of the mixture, and especially the pressure and temperature, (3) the type of ignition, (4) whether the mixture is turbulent or not. In the gas or petrol engine the turbulence of the explosive mixture, due to its rapid entry into the cylinder, assists the explosion and makes it more rapid. When **detonation** occurs each successive layer of explosive mixture is ignited by the heat of compression of an explosive wave travelling at about 8000 ft. per sec. Hence in this case the combustion is vastly quicker than with ordinary explosions, and it produces the effect known as **knocking** when it occurs in the internal combustion engine.

Temperature and heat. The distinction between *quantity* of heat and *intensity* of heat must be clearly understood. Irrespective of the quantities of hot or cold water, it is possible to estimate roughly, by the sense of touch, the intensity of heat or temperature of each. To measure temperatures more accurately a thermometer is used. The uniform expansion of substances, such as mercury, with rise of temperature, provides an excellent and ready means of measuring temperature. To standardise thermometers, fixed points are chosen, namely, the freezing and boiling points of pure water when the pressure is that due to 30 in. of mercury (see p. 30). For higher temperatures the boiling points of sulphur and mercury provide fixed points, and since the boiling point of a liquid depends on the pressure, this must also be standardised. The fixed points mark the main points on the thermometer scale, which for convenience is divided into a large number of divisions or degrees. Fig. 1 shows

a comparison between the two best known thermometer scales, namely the Fahrenheit and Centigrade. A graph is also shown

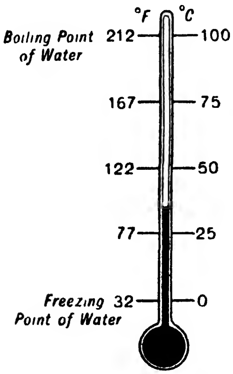


FIG. 1. Mercury thermometer showing Fahrenheit and Centigrade scales.

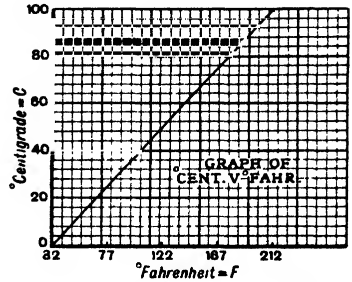


FIG. 2. Equation of graph $F = 1\frac{4}{5}C + 32$.

(Fig. 2), which may be used for the conversion of temperature readings from one scale to another. The equation $F = 1\frac{4}{5}C + 32$ may also be used for conversion.

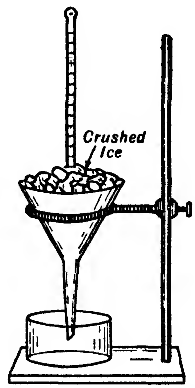


FIG. 3. Thermometer in ice for the observation of freezing point.

EXPT. 2.

OBJECT. *To mark the higher and lower fixed points on a mercury thermometer.*

METHOD OF PROCEDURE. (*a*) *The lower fixed point or freezing point.* Prepare a supply of finely broken ice which has been thoroughly washed. Place this in the form of a close pack in a funnel (Fig. 3), and through the centre insert a pencil to prepare a place for the thermometer: make sure the drainage hole is free and insert the thermometer into the pack. Allow the thermometer to remain in the ice pack for some time, until it can be regarded as registering the temperature of melting ice. The thermometer is then raised until the mercury is just visible and a slight scratch placed on the tube at the mercury

level. The trade process is to mark this scratch on a thin layer of wax " resist " or varnish and then etch the glass in the vapour of hydrofluoric acid, which has the special property of attacking glass.

(*b*) *The higher fixed point or boiling point.* The process of marking this fixed point depends upon obtaining the temperature of steam produced from boiling water, but it must be remembered that the temperature of formation of steam depends on the barometric pressure. In order to obtain a true marking it is thus necessary that the experiment be performed when the barometer reading is as near as possible to 760 mm., otherwise a correction will have to be applied for the variation of pressure. A glass tube fitted into a flask (Fig. 4) is surrounded by a large diameter tube fitted with a cork bored to receive the thermometer. The steam passes through the inner tube, which is shorter than the outer and contains the thermometer, and is then exhausted through an outlet in the bottom of the outer tube. The thermometer is freely fitted to the cork of the outer tube, and it is prevented from falling through the cork by a rubber band fitted to it above the cork. Thus the whole of the mercury in the thermometer is immersed in the steam passing through the inner tube, but is not in contact with the water from which the steam is formed. When the thermometer has a settled registration of the temperature of the steam it is raised sufficiently to mark the stem at the mercury level. The thermometer may then be completely graduated by fixing it to a wooden base and subdividing the distance between the higher and lower fixed points to show degrees Centigrade or Fahrenheit.

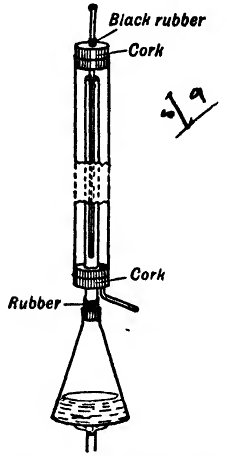


FIG. 4. Apparatus for determining the boiling point on a thermometer.

NOTE.—In the process of preparation of a mercury thermometer the end is sealed while the mercury is at such a temperature that it fills the whole of the thermometer stem, and the walls of the stem are of such a thickness that they will withstand the external air pressure on cooling. If this precaution were not taken there would be air above the mercury, and this would tend to burst the thermometer with increase of temperature and pressure. An enlargement of the bore at the top of a thermometer will also prevent bursting

by the expanding liquid should the thermometer be accidentally raised above its normal maximum reading.

Examples on the conversion of temperatures.

Example 1. *The boiling and freezing points of turpentine are respectively* 159° *C. and* − 10° *C. Convert these temperatures to the Fahrenheit scale.*

Fahrenheit reading $= \frac{9}{5}$(Centigrade reading) + 32.

This is because 0° C. is equivalent to 32° F. and 100 Cen. degrees are equivalent to 180 Fahr. degrees.

As an algebraic equation,

$$F = \tfrac{9}{5}C + 32.$$

For $C = 159°$, $F = \frac{9}{5} \times 159 + 32 = 318{\cdot}2°$.

For $C = -10°$, $F = \frac{9}{5} \times (-10) + 32 = -18 + 32 = 14°$.

Thus to convert to Fahrenheit temperature, multiply the Centigrade temperature by $\frac{9}{5}$ and then add 32.

Example 2. *The melting points of glass, cast iron and tin are respectively* 2012° *F.*, 2192° *F. and* 450° *F. What are these temperatures on the Centigrade scale?*

In these cases the procedure must be reversed.

Thus to convert to Centigrade temperature, subtract 32 from the Fahrenheit temperature and then multiply by $\frac{5}{9}$.

As an algebraic equation, $C = \frac{5}{9}(F - 32)$.

For $F = 2012$, $C = \frac{5}{9}(2012 - 32) = \frac{5}{9} \times 1980 = 1100°$.

For $F = 2192$, $C = \frac{5}{9}(2192 - 32) = \frac{5}{9} \times 2160 = 1200°$.

For $F = 450$, $C = \frac{5}{9}(450 - 32) = \frac{5}{9} \times 418 = 232\frac{2}{9}°$.

Example 3. *Ammonia and carbon dioxide liquefy at* − 28·3° *F. and* 109° *F. respectively. Convert these temperatures to the Centigrade scale.*

For $F = -28{\cdot}3°$, $C = \frac{5}{9}(F - 32) = \frac{5}{9}(-28{\cdot}3 - 32) = \frac{5}{9} \times -60{\cdot}3 = -33{\cdot}5°$.

For $F = -109°$, $C = \frac{5}{9}(-109 - 32) = \frac{5}{9}(-141) = -78\frac{1}{3}°$.

Effect of heat on the dimensions. Certain alloys keep their original dimensions when heated over a considerable range of temperature, but most materials increase in size when heated, while a few decrease. Change of dimension occurs in all directions, and expansion or contraction is referred to as linear if considered in one direction only, superficial if change of area is considered, and cubical for change of volume.

The **coefficient of linear expansion** for a material, when heated uniformly, is the average increase in any dimension, per degree rise in temperature, per unit of length. This coefficient will be larger in Centigrade units than in Fahrenheit units, as the former unit is larger, in the ratio 9 : 5. The coefficients of superficial and cubical expansions are taken, in engineering practice, as respectively *double* and *treble* the coefficient of linear expansion.

Let a metal cube of side l in. be raised in temperature 1° F., and the coefficient of linear expansion of the material be α.

New length of each edge $= l + l \times \alpha \times 1 = l(1+\alpha)$.

New area of each face $= l(1+\alpha) \times l(1+\alpha)$

$= l^2(1 + 2\alpha + \alpha^2)$

$= l^2(1+2\alpha)$, if α^2 is neglected in comparison with α, which is very small.

∴ Increase in area of each face $= l^2 + 2\alpha l^2 - l^2 = 2\alpha l^2$.

$$\text{Coefficient of superficial expansion} = \frac{\text{increase of area}}{\text{original area} \times \text{rise of temp.}}$$

$$= \frac{2\alpha l^2}{l^2 \times 1} = 2\alpha$$

$= 2 \times$ **coefficient of linear expansion.**

Similarly,

New volume of cube $= [l(1+\alpha)]^3 = l^3(1 + 3\alpha + 3\alpha^2 + \alpha^3)$.

Increase in volume $= l^3(1+3\alpha) - l^3$, if powers of α are neglected in comparison with α,

$= l^3 + 3l^3\alpha - l^3 = 3l^3\alpha$.

$$\text{Coefficient of cubical expansion} = \frac{\text{increase of volume}}{\text{original volume} \times \text{rise of temp.}}$$

$$= \frac{3l^3\alpha}{l^3} = 3\alpha$$

$= 3 \times$ **coefficient of linear expansion.**

Thus,

Increase of area $=$ **original area** $\times$ **rise in temp.** $\times\, 2\alpha$.

Increase of volume $=$ **original volume** $\times$ **rise in temp.** $\times\, 3\alpha$.

It will be noted that in deriving these results all powers of α in excess of 1 have been neglected. This is justifiable in practice, for

if $\alpha=0{\cdot}001$, $\alpha^2=0{\cdot}000001$ and $\alpha^3=0{\cdot}000000001$, quantities which are negligible in comparison with 0·001.

The alteration in dimensions due to temperature change has always to be allowed for in practical work in all branches of engineering. To quote a few examples, there is the allowance to be made for the shrinkage in castings after cooling, the expansion bends and joints to provide for the increase in length of steam pipes, the gaps left between the rails on the railway and at the end of long bridges to allow for the differences of length under conditions of summer and winter temperatures. If allowance is not made and the natural expansion is restricted the material is stressed accordingly, with perhaps disastrous consequences. Sometimes the difference in the rates of expansion of two different materials is utilised in the making of a secure fastening, such as the shrinkage of a steel tyre on a wheel. The tyre is bored slightly smaller than the wheel and heated sufficiently to be fitted on. After cooling the shrinkage or contraction causes a very tight and binding fit between tyre and wheel. The principle is widely utilised, especially in the construction of big guns, flywheels, thick cylinders and fastenings generally.

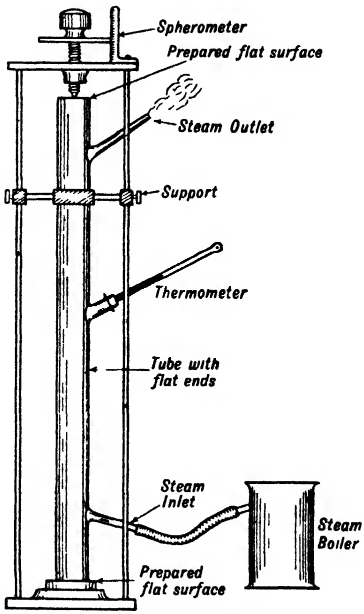


FIG. 5. Linear expansion.

EXPT. 3. **Expansion of solids.**

OBJECTS. *To determine the coefficient of linear expansion of copper, brass and aluminium.*

APPARATUS. The apparatus (Fig. 5) consists of a cast iron base with a prepared flat top surface; two rods attached to this base carry a crosshead, to which is fitted a spherometer to read to $\frac{1}{1000}$ in. A sliding support is adjustable to any position along the rods. The specimens consist of tubes about $\frac{3}{8}$ in. diameter and 18 in. in length,

with their ends sealed by means of flat plates surfaced to two flat surfaces. Steam inlet and exhaust tubes are fitted to these specimens, and a thermometer pocket is inserted to carry the thermometer . Steam is passed from the boiler through the inlet tube and exhausted into the atmosphere.

METHOD OF PROCEDURE. Clean the flat surfaces of the tube ends and the base plate. Adjust and read the spherometer just to make contact with the tube end, and note the temperature before the steam is admitted. *Slack back the spherometer* so that the tube has freedom to expand without damage to the instrument, and then allow the steam to pass through the tube until the thermometer registers a steady temperature. Now screw down the spherometer just to make contact again with the tube end, note the reading and subtract from this reading the initial reading. This quantity is then the linear expansion of the tube. Repeat the experiment for the brass and aluminium tubes.

OBSERVATIONS. Length of tube = 18 in.

Observation	Copper	Brass	Aluminium
Initial spherometer reading	0·357 in.	0·376 in.	0·325 in.
Final spherometer reading -	0·379 in.	0·401 in.	0·354 in.
Expansion - - -	0·022 in.	0·025 in.	0·029 in.
Initial temperature - -	18° C.	18° C.	18° C.
Final temperature - -	90° C.	91° C.	90° C.
Rise in temperature - -	72° C.	73° C.	72° C.

DERIVED RESULTS. The coefficient of linear expansion is the expansion per unit length per Cen. degree rise in temperature.

Thus the coefficient of linear expansion is

$$\frac{\text{expansion (in.)}}{\text{length (in.)} \times \text{rise in temp. (° C.)}} = \alpha.$$

In comparing the following results it is worthy of note that an alloy of iron and nickel (known as **invar**) used in clock and instrument making has the value for α of only 0·0000012 per Cen. degree. Values of α for cast iron, wrought iron, nickel, steel and glass tube are respectively 0·0000106, 0·00001139, 0·00001019, 0·00001321, 0·00000833 per Cen. degree.

Copper - - -	$\alpha = \frac{0{\cdot}022}{18 \times 72} = 0{\cdot}000017$
Brass - - -	$\alpha = \frac{0{\cdot}025}{18 \times 73} = 0{\cdot}000019$
Aluminium - -	$\alpha = \frac{0{\cdot}029}{18 \times 72} = 0{\cdot}0000224$

NOTE.—*The correct values for the coefficient of linear expansion are as follow. Copper* 0·0000168, *Brass* 0·0000187, *Aluminium* 0·0000222 *per degree Centigrade.*

Example 1. *A steam pipe is* 50 *ft. long at* 50° *F. What is its length when full of steam at* 700° *F.? Take* α *as* 0·0000066. *Assume* 700° *F. is the temperature of the pipe.*

$$\text{Increase in length} = 50 \times 0{\cdot}0000066 \times 650$$
$$= 0{\cdot}2145 \text{ ft.}$$
$$\text{New length} = \mathbf{50{\cdot}2145 \text{ ft.}}$$

Example 2. *The two halves of the boss of a flywheel are joined together by two rings shrunk on the ends. If the boss is* 6 *in. in external diameter and the internal diameter of the rings* 5·988 *in., calculate the lowest range of temperature through which the rings must be heated in order to be fitted to the boss.* $\alpha = 0{\cdot}0000066$.

Since the diameter is proportional to the circumference, this problem is really one of increase of diameter.

Increase of diameter $= 6 - 5{\cdot}988$ in. $= 0{\cdot}012$ in.

$\therefore\ 5{\cdot}988 \times 0{\cdot}0000066 \times \text{rise in temp.} = 0{\cdot}012$;

$$\text{or, rise in temp.} = \frac{0{\cdot}012}{5{\cdot}988 \times 0{\cdot}0000066} = \mathbf{304° \text{ F.}}$$

Example 3. *If the boss in Example* 2 *is assumed to be unyielding, what is the approximate circumferential strain and stress in the rings.* $E =$ *Young's modulus* $= 30 \times 10^6$ *lb. per sq. in.*

$$\text{Strain} = \frac{\text{Change in circumference}}{\text{Original circumference}}$$
$$= \frac{0{\cdot}012\pi}{5{\cdot}988\pi} = \mathbf{0{\cdot}002 \text{ nearly.}}$$

$$\text{Stress} = E \times \text{strain} = 30 \times 10^6 \times 0{\cdot}002 = \mathbf{60{,}000 \text{ lb. per sq. in.}}$$

Example 4. *A steam pipe, 10 ft. long, at 50° F. is filled with steam at 500° F. Find the increase in length if the linear coefficient of expansion for the metal of the pipe is 0·000012 per Cen. degree. Find the new area of a butterfly valve in this pipe if its original area was 27 sq. in.*

Coefficient of expansion per ° F. $= 0{\cdot}000012 \times \frac{5}{9} = 0{\cdot}00000667$.

Increase in length = original length × rise of temp. × coefficient

$$= 10 \times 450 \times 0{\cdot}00000667 = 0{\cdot}03 \text{ ft.} = \mathbf{0{\cdot}36 \text{ in.}}$$

Coefficient of superficial expansion $= 0{\cdot}00000667 \times 2 = 0{\cdot}00001334$.

New area $= 27 + 27 \times 450 \times 0{\cdot}00001334 = 27 + 0{\cdot}1617 =$ **27·162 sq. in.**

Example 5. *Calculate the density of a specimen of copper at 620° C. if at 20° C. its density is 526 lb. per cu. ft. $\alpha = 0{\cdot}0000504$ per Cen. degree, where α is the coefficient of cubical expansion.*

1 cu. ft. at 20° C. will become $1 + 1 \times 600 \times 0{\cdot}0000504$ cu. ft. at 620° C.

$$= 1{\cdot}03024 \text{ cu. ft.}$$

1·03024 cu. ft. at 620° C. weighs 526 lb.

$$\therefore \ 1 \text{ cu. ft. at } 620° \text{ C. weighs } \frac{526}{1{\cdot}03024} = \mathbf{510{\cdot}6 \text{ lb.}}$$

The continued application of heat when a certain point is reached will probably produce a change of state as well as a change of dimensions. This effect of heat is dealt with on p. 22. Also the effect of heat on metals plays a vital part in the processes of hardening, normalising, annealing, welding and forging, and makes it imperative for the engineer to have a knowledge of the methods of the measurement of temperature and of heat quantities.

Measurement of heat quantities. Simple physical experiments in mixing different masses of liquids and solids at varying temperatures show that three things are required to estimate the quantity of heat a body possesses. These are: (1) the nature of the material composing the body, (2) the mass of the body, and (3) the temperature. Thus if the mass of a body is unaltered, and it does not change its state, the quantity of heat it possesses is approximately proportional to its temperature. The heat units employed are generally as follow.

(1) The **British Thermal Unit (B.Th.U.)** is the quantity of heat required to raise 1 lb. of water through a Fahr. degree. Strictly speaking, it

is $\frac{1}{180}$th of the quantity of heat required to raise 1 lb. of water from 32° F. to 212° F., because the amount of heat required varies slightly with the temperature.

(2) The **gram-calorie** is the amount of heat required to raise 1 gram of pure water from 0° to 1° C.

(3) The **Centigrade heat unit (C.H.U.)** or **pound calorie** is $\frac{1}{100}$th of the amount of heat required to raise 1 lb. of water from 0° C. to 100° C.

(4) The **Therm** is equivalent to 100,000 B.Th.U., and is the unit of supply of energy in the gas industry.

Since the units of mass are the same for both the B.Th.U. and the C.H.U. and 1 Cen. degree $=1{\cdot}8$ Fahr. degree, then 1 C.H.U. is equivalent to 1·8 B.Th.U. The difference between the C.H.U. and the gram calorie is principally in the unit of mass. Therefore 1 C.H.U. is equivalent to 453·6 gram calories because 1 lb. $=453{\cdot}6$ grams.

It is important to notice that if a gram of substance contains h gram calories, then 1 lb. of the same substance under the same conditions contains h C.H.U. or $1{\cdot}8\,h$ B.Th.U.

The amount of heat required to raise the temperature of 1 lb. of a substance through 1° is often called the **specific heat** of the substance. Also the specific heat of a substance is frequently regarded as the ratio

$$\frac{\text{heat to raise the substance } 1^\circ}{\text{heat to raise the same mass of water } 1^\circ}.$$

The specific heats of a few substances are given in the following table:

Substance	Specific heat	Substance	Specific heat
Water - - -	1	Flue gases at constant pressure -	0·25
Steam at constant pressure at 100° C. -	0·465	Air at constant pressure - - -	0·2375
Sea water - - -	0·94	Cast iron - -	0·119
Alcohol - - -	0·55	Copper - - -	0·0936
Mercury - - -	0·033	Aluminium - -	0·219

Loss or gain of heat is measured by the product

mass of body × specific heat of body × change of temperature.

The water equivalent of a calorimeter is the quantity of water which will have the same heat capacity as the calorimeter. This quantity will be the weight of the calorimeter times the specific heat of the material from which it is made. In this case the water equivalent is $W_2 \times S$ grams.

NOTE. It is general to make calorimeters of spun copper or aluminium. The specific heat of copper is generally taken as 0·094 and that of aluminium as 0·219.

EXPT. 4. **Introduction to the method of mixtures.**

OBJECT. *To verify the principle that the total heat of a mixture is, immediately after mixing, equal to the sum of the total heats of its constituents before mixing.*

APPARATUS. Two calorimeters, a stirrer, thermometer, a balance and weights.

METHOD OF PROCEDURE. Weigh each of the calorimeters, when dry and empty, and about one quarter fill each with water. Find by weighing the weight of water in each calorimeter, and determine the water equivalent of the second calorimeter by multiplying its weight by the specific heat of copper 0·094. Heat the water in the first calorimeter A to about 80° C. and note the temperature of the water in each calorimeter. Pour the contents of the first calorimeter into the second, stir and note the final temperature. Then the total heat possessed by the second calorimeter and its contents, after mixing, should be equal to the heat possessed by the second calorimeter and its contents together with the heat possessed by the water in the first calorimeter before mixing.

OBSERVATIONS.

Weight of calorimeter B	= 57·3 gm.
Weight of calorimeter B + water	= 119·4 gm.
Weight of water in B	= 62·1 gm.
Water equivalent of B	= 57·3 × 0·094
	= 5·4 gm.
Temperature of B before mixing	= 16° C.

(*X*) *Total heat of B* $= 16(62{\cdot}1 + 5{\cdot}4) = 16 \times 67{\cdot}5$
$= 1080$ *calories.*

Weight of calorimeter A $= 63{\cdot}1$ gm.
Weight of calorimeter A + water $= 124{\cdot}9$ gm.
Weight of water in A $= 61{\cdot}8$ gm.
Temperature of A before mixing $= 78°$ C.

(*Y*) *Total heat of water in A* $= 78 \times 61{\cdot}8$
$= 4820{\cdot}4$ *calories.*

After mixing:

Weight of water in B $= 62{\cdot}1 + 61{\cdot}8$
$= 123{\cdot}9$ gm.
Temperature of B $= 45°$ C.

(*Z*) *Final total heat of B* $= (123{\cdot}9 + 5{\cdot}4)45$
$= 5818{\cdot}5$ *calories.*

This should be equal to $X + Y$, that is,

$$X + Y = Z,$$

or

$$1080 + 4820{\cdot}4 = Z.$$
$$5900{\cdot}4 = Z.$$

Thus the difference between 5900·4 and 5818·5 calories are lost in the process of mixing, probably due to observational errors and losses of heat to the surroundings.

Expt. 5. **An extension to Expt. 4.**

Objects. *To perform Experiment 4, using a coil of iron wire of weight equal to the water in the first calorimeter.*

Method of procedure. Repeat Experiment No. 4, this time using a coil of iron wire of the same weight as the water, immersed in the water of the first calorimeter. Arrange for the same weight of water in the second calorimeter, and the same initial temperatures in each calorimeter. Transfer the iron coil to the second calorimeter, stir and notice the final temperature. Answer the following questions: (1) Is the final temperature of the water higher or lower than in Experiment No. 4? (2) Why is the resulting temperature different? Hence calculate the specific heat of iron (see Expt. 6.).

Expt. 6. **Specific heat of solids.**

Objects. (*a*) *To find the specific heat of copper.*

(*b*) *To find the water equivalent of a calorimeter.*

Apparatus. A copper calorimeter (Fig. 6), thermometer, suitable lagging, and an accurate spring balance to read in lb.; a piece of

copper rod suspended from a light string or cotton, a beaker, bunsen and tripod.

METHOD OF PROCEDURE. Weigh the copper calorimeter after it has been thoroughly cleaned and dried. About half-fill the calorimeter with water and again weigh; hence determine the weight of water in the calorimeter. Stand the calorimeter in a box or large beaker and surround it with cotton wool or some suitable lagging to help to prevent transfer of heat to the air. Next heat a beaker of water to a temperature approaching boiling point, and suspend the copper rod in this water after determining the weight of the copper. Take the temperature of the water in the beaker and that of the water in the calorimeter, then transfer the copper to the calorimeter, shaking clear any surplus water before immersing. Stir quickly the water in the calorimeter and take its final temperature.

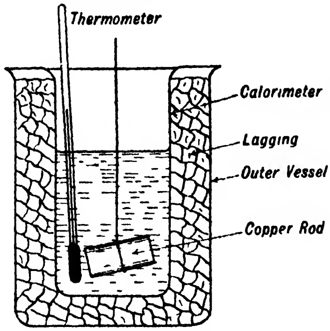


FIG. 6. Specific heat of a solid.

THEORY OF SPECIFIC HEAT BY MIXTURE. The copper rod will, before transfer, contain a certain quantity of heat which, after transfer, will be shared between (*a*) the copper of the calorimeter, (*b*) the water in the calorimeter, (*c*) the rod itself. So that *the heat gained by the water and the calorimeter will be equal to the heat lost by the copper rod if losses are neglected.*

OBSERVATIONS.

Initial temperature of water and calorimeter $= t_1^\circ$ C.
Temperature of copper before transfer $= t_2^\circ$ C.
Temperature of water in calorimeter (final) $= t_3^\circ$ C.
Weight of copper rod $= W_1$ gm.
Weight of empty calorimeter $= W_2$ gm.
Weight of calorimeter + water $= W_3$ gm.
Weight of water in calorimeter $= (W_3 - W_2)$ gm.

DERIVED RESULTS.

(*a*) Heat lost by copper $= W_1(t_2 - t_3) \times S$ calories, where S is the specific heat of copper.

(*b*) Heat gained by calorimeter $= W_2(t_3 - t_1) \times S$ calories.

(c) *Heat gained by water* $= (W_3 - W_2)(t_3 - t_1) \times 1$ calories where the specific heat of water is unity.

Now the heat equation becomes

$$(a) = (b) + (c),$$

or
$$W_1 S (t_2 - t_3) = W_2 S (t_3 - t_1) + (W_3 - W_2)(t_3 - t_1)$$

and
$$S = \frac{(W_3 - W_2)(t_3 - t_1)}{W_1(t_2 - t_3) - W_2(t_3 - t_1)}.$$

EXPT. 7. **Specific heat of solids.**

OBJECT. *To find the specific heat of iron, using a copper calorimeter.*

METHOD OF PROCEDURE. This experiment is conducted on similar lines to the previous experiment. The specific heat of copper is assumed to be 0·094, and the water equivalent of the calorimeter is then taken as 0·094 × its weight.

OBSERVATIONS.

Initial temperature of water	$= t_1°$ C. = 18° C.
Initial temperature of iron	$= t_2°$ C. = 98° C.
Final temperature of mixture	$= t_3°$ C. = 25° C.
Rise in temperature of the water	$= (t_3 - t_1) = 7°$ C.
Fall in temperature of the iron	$= (t_2 - t_3) = 73°$ C.
Weight of iron rod	$= W_1$ gm. = 95·5 gm.
Weight of empty calorimeter	= 41·4 gm. = W_2 gm.
Weight of water + calorimeter	= 159·4 gm. = W_3 gm.
Weight of water in calorimeter	= 118 gm. = $(W_3 - W_2)$ gm.

DERIVED RESULTS.

Let S be the specific heat of iron.

Water equivalent of calorimeter	$= 0{\cdot}094 W_2$.
	= 3·89 gm.
Heat given to water and calorimeter	= 121·89 × 7 = 853·2 cal.
Heat given up by iron	$= W_1 \times (t_2 - t_3) \times S$ cal.
	= 95·5 × 73 × S calories.

Heat gained by calorimeter and water = heat lost by the iron.

$$853{\cdot}2 = 95{\cdot}5 \times 73 \times S.$$

$$S = \frac{853{\cdot}2}{95{\cdot}5 \times 73} = 0{\cdot}123.$$

EXPT. 8. **Specific heat of liquids.**

OBJECT. *To determine the specific heat of oil.*

APPARATUS. The apparatus for this experiment is a copper calorimeter and a piece of copper or iron of known specific heat.

METHOD OF PROCEDURE. The same observations have to be taken for this experiment as in the previous experiments on specific heat of solids. In place of water in the calorimeter a quantity of oil is employed, and the heat gained by the calorimeter and the oil is equal to the heat lost by the piece of copper or iron.

OBSERVATIONS.

Weight of empty calorimeter	= 41·4 gm.
Weight of calorimeter and oil	= 136·6 gm.
Weight of oil	= 95·2 gm.
Initial temperature of oil	= 18° C.
Initial temperature of copper	= 98° C.
Final temperature of copper and oil	= 26° C.
Fall of temperature of copper	= 72° C.
Rise of temperature of oil	= 8° C.
Weight of copper	= 57 gm.

DERIVED RESULTS.

Let S be the specific heat of the oil.

Water equivalent of calorimeter $= 41{\cdot}4 \times 0{\cdot}094 = 3{\cdot}89$ gm.

Heat given to calorimeter and oil $= 3{\cdot}89 \times 1 \times 8 + 95{\cdot}2 \times S \times 8$, where the specific heat of water is unity.

Heat lost by copper $= 57 \times 72 \times 0{\cdot}094$, where $0{\cdot}094$ is the specific heat of copper.

Then
$$3{\cdot}89 \times 8 + 95{\cdot}2 \times 8 \times S = 57 \times 72 \times 0{\cdot}094,$$
$$31{\cdot}12 + 761{\cdot}6S = 385{\cdot}78,$$
$$761{\cdot}6S = 354{\cdot}66,$$
$$S = 0{\cdot}465.$$

Example 1. *If 40 lb. of metal required 62 C.H.U. to raise its temperature from 46° F. to 136° F., calculate the specific heat of the metal.*

Rise of temperature $= 136°$ F. $- 46°$ F. $= 90 \times \frac{5}{9}$ or 50 Cen. degrees.

Heat required = 62 C.H.U. $= 40 \times 50 \times$ specific heat.

$$\therefore \text{ specific heat} = \frac{62}{40 \times 50} = 0{\cdot}031.$$

Example 2. *Air is supplied to a furnace at a temperature of 100° F. at the rate of 18 lb. of air to 1 lb. of fuel, and the spent gases leave the flue at 500° F. Calculate the heat energy lost per lb. of fuel.*

Mass of products of combustion = Wt. of air + Wt. of fuel
= 18 + 1 = 19 lb.

Specific heat of gases (approx.) = 0·25 (see table p. 15).

Rise of temperature = 500° − 100° = 400° F.

∴ Heat energy lost up chimney per lb. of fuel
= mass × specific heat × temp. rise
= 19 × 0·25 × 400 = **1900 B.Th.U.**

Or, $\frac{5}{9} \times 1900 =$ **$1055\frac{5}{9}$ C.H.U.**

Example 3. *If carbon monoxide produces 4390 B.Th.U. per lb. when it is burnt, and if it requires $2\frac{1}{2}$ lb. of air as a minimum for complete combustion, estimate the highest temperature that could be reached. Take the specific heat of the gases as 0·25 and neglect all losses.*

Equate the heat available to the heat gained by the spent gases, and assume the specific heat remains constant.

Total mass of gas × specific heat × rise of temp. = 4390 B.Th.U.

$$3\tfrac{1}{2} \times 0{\cdot}25 \times t = 4390.$$

$$t = \frac{4390}{3\frac{1}{2} \times \frac{1}{4}} = 5017.$$ **Ans. 5017 Fah. degrees above air temp.**

Owing to losses this could not be attained in practice.

Example 4. *Convert 1 therm, 1 B.Th.U. and 1 C.H.U. to gram calorie heat units, given that 1 lb. = 453·6 gm. Also determine the number of gram calories equivalent to 1 B.Th.U.*

1 B.Th.U. is equivalent to 1 lb. of water through 1 Fahr. degree,

or 453·6 gm. of water through 1 Fahr. degree,

or $\frac{453{\cdot}6}{1{\cdot}8}$ gm. of water through 1 Cen. degree.

= **252 gram calories.**

1 B.Th.U. is equivalent to $\frac{5}{9}$ of a C.H.U., since 1 Fahr. degree = $\frac{5}{9}$ Cen. degree.

∴ 1 C.H.U. is equivalent to $\frac{9}{5} \times 252 =$ **453·6 gram calories.**

1 Therm = 100,000 B.Th.U. = **252×10^5 gram calories.**

Also, since 1 B.Th.U. = 252 gram calories,

then 1 gram calorie = $\frac{1}{252}$ or **0·003968 B.Th.U.**

Example 5. *A cylinder contains 2 cu. ft. of coal gas which if reduced to normal temperature and pressure (N.T.P., see p. 39) would occupy 200 cu. ft. If each cu. ft. at N.T.P. produces 500 B.Th.U. when it is burnt, calculate the number of B.Th.U., therms and C.H.U. available in this quantity of gas.*

$$\text{No. of B.Th.U.} = 200 \times 500 = \mathbf{100{,}000}$$
$$= \mathbf{1\ therm.}$$
$$\text{No. of C.H.U.} = \tfrac{5}{9} \times 100{,}000 = \mathbf{55{,}555\tfrac{5}{9}}.$$

Example 6. *The weight of metal in the pipes, thermal storage tanks, heaters, etc., in the hot water system of a house is 420 lb. and the weight of water is 3000 lb. Calculate the water equivalent of the system. Specific heat of metal* $= 0{\cdot}11$.

Water equivalent of metal $= 420 \times 0{\cdot}11 = 46{\cdot}2$ lb.
Wt. of water $= 3000$ lb.
Total $= \mathbf{3046{\cdot}2}$ **lb.**

Example 7. *The dry flue gases leaving the air pre-heater of a boiler consist of* $13{\cdot}4\%$ *of carbon dioxide,* $5{\cdot}5\%$ *of oxygen and* $81{\cdot}1\%$ *of nitrogen, and their temperature is* $277°$ *F. If their specific heats are respectively* $0{\cdot}212$, $0{\cdot}218$ *and* $0{\cdot}248$, *calculate the heat lost to the chimney above* $60°$ *F. per lb. of dry flue gas. What is the average specific heat of the gases?*

1 lb. of dry flue gas contains :

0·134 lb. of CO_2 containing $0{\cdot}134 \times 0{\cdot}212 \times (277 - 60)$ or $6{\cdot}164$ B.Th.U.
0·055 lb. of O_2 containing $0{\cdot}055 \times 0{\cdot}218 \times (277 - 60)$ or $2{\cdot}602$ B.Th.U.
0·81 lb. of N_2 containing $0{\cdot}81 \times 0{\cdot}248 \times (277 - 60)$ or $43{\cdot}591$ B.Th.U.
Total $= \mathbf{52{\cdot}357}$ **B.Th.U.**

$$\text{Average specific heat} = \frac{\text{total heat}}{\text{mass} \times \text{temp. change}} = \frac{52{\cdot}357}{1 \times 217} = \mathbf{0{\cdot}241}.$$

Change of state. Nearly every substance, under suitable conditions of pressure and temperature, can exist in one of three states as gas, liquid or solid. For example, steam, water and ice are the same chemical substance in three different physical states.

Sensible heat is the name given to the heat received by or abstracted from a solid or liquid which produces a rise or fall of temperature. Hence a thermometer will record the receipt or loss of sensible heat and make it evident to the senses. A solid can absorb sensible heat until its temperature of melting or **melting**

point is reached, while a liquid can absorb sensible heat until its temperature of vaporisation or **boiling point** is reached.

Both at the melting point of a solid and at the boiling point of a liquid considerable quantities of heat are required to change the state of the substance, that is, either to melt or vaporise it. Similarly considerable quantities of heat must be abstracted to freeze a liquid or liquefy a vapour. This heat is called **latent heat**, and *the thermometer records no change until all the substance has been melted, vaporised, frozen or liquefied as the case may be.*

At atmospheric pressure, change of state takes place at a temperature which is characteristic of the substance, and this fact is utilised in the determination of the fixed points on thermometers. Different substances require different quantities of latent heat to produce a change of state, but the amount is always exactly the same for any given pure substance under the same physical conditions. The presence of impurities alters the characteristic temperature at which the pure substance changes state, and also varies the amount of latent heat required to produce the change of state. A change of pressure also varies the temperature of change of state, more especially that of the boiling point, and the quantity of latent heat required ; but it should be realised that, under a given set of conditions, no change of state can be effected without the addition or subtraction of a *fixed* quantity of heat known as the latent heat which is associated with that particular change of state.

In the case of alloys or mixtures the change of state of each constituent occurs at its appropriate temperature, and thus in the cooling curve of an alloy two or more periods of change of state are shown.

The **latent heat of fusion** of a substance is the quantity of heat which must be given to unit mass to change it from a solid to a liquid (*i.e.* to melt it), or subtracted to change it from a liquid to a solid (*i.e.* to freeze it).

The **latent heat of vaporisation** or **evaporation** of a substance is the quantity of heat which must be given to unit mass to change it from a liquid to a vapour (*i.e.* to evaporate it), or abstracted to change it from a vapour to a liquid (*i.e.* to condense it).

Thus, if L units of heat is the latent heat of 1 lb. of a certain substance at the temperature and pressure corresponding to a change of

state, then x units of heat applied or abstracted when the substance is at that temperature and pressure will change the state of $\frac{x}{L}$ lb. of the substance. This is true even when x is a very small quantity.

When specifying the quantity of sensible heat a body possesses, the **base** or **datum temperature** must be given, above which the heat is reckoned.

In specifying latent heat quantities care must be given to state: (*a*) the kind of substance and its condition (*b*) the pressure or temperature, since one depends on the other, (*c*) the nature of the change of state, (*d*) the units of mass and temperature employed.

The following are examples of complete statements:

The latent heat of vaporisation of steam at 1000 lb. per sq. in. absolute is 660·2 B.Th.U. per lb.

The latent heat of evaporation of carbon dioxide at 760 mm. of mercury is 137·9 gm. cal. per gm.

The sensible heat contained by 1 lb. of iron at 100° C. is

$$1 \times 0{\cdot}119 \times 80$$

or 9·52 C.H.U. reckoned above a base temperature of 20° C., or $1 \times 0{\cdot}119 \times 100$ or 11·9 C.H.U. reckoned above a base temperature of 0° C.

It is worthy of notice that James Watt first pointed out that when a certain weight of steam at 212° F. was passed from a kettle into a jar of cold water, the steam raised nearly six times its weight of cold water to boiling point (212° F.). In hot countries drinking water is stored in unglazed or slightly porous vessels, the heat necessary for the evaporation of water from the surface of the vessel, being abstracted from the water within, thus keeping it cool. In a similar way, even in strong sunlight, a wet blanket surrounding ice will preserve the ice in a solid condition, providing the water from the blanket is allowed to evaporate freely. In fact, the lowering of the boiling point of liquids with the pressure, and the absorption of heat from the surrounding medium necessary to produce evaporation at that pressure, is the main principle of the modern refrigerating machine. The vapours generally employed are those of ammonia and carbon dioxide.

As with specific heat, the latent heats of substances, their melting and their boiling points must be determined by experiment with apparatus of a refined nature.

EXPT. 9. **Change of state.**

OBJECT. *To find the latent heat of fusion of ice.*

APPARATUS. A copper calorimeter, some broken ice and a thermometer.

METHOD OF PROCEDURE. Weigh the calorimeter, and add to the calorimeter about one half its capacity of water. Find the weight of the water by weighing the calorimeter plus water and subtracting the weight of the calorimeter. Heat the calorimeter and water to about 40° C. and dry the ice thoroughly. Note the temperature of the water. Immerse the ice in the water, stir thoroughly until all the ice is melted, and note the final temperature of the water. Then weigh the calorimeter plus water plus melted ice.

OBSERVATIONS.

Weight of empty calorimeter	= 41·4 gm.
Weight of calorimeter + water	= 123·7 gm.
Weight of water	= 82·3 gm.
Weight of ice	= 16·1 gm.
Initial temperature of water	= 40° C.
Final temperature of water	= 21° C.
Fall of temperature of water	= 19° C.

DERIVED RESULTS. When the ice is added to the water the ice melts and absorbs heat according to its latent heat of fusion. Thus: *Heat lost by the calorimeter and the water = latent heat required to melt the ice + heat required to raise the temperature of the melted ice to the final temperature of the water.*

Let L be the latent heat of ice.

Water equivalent of the calorimeter $= 41{\cdot}4 \times 0{\cdot}094 = 3{\cdot}89$ gm.

Then
$$(82{\cdot}3 + 3{\cdot}89)(40 - 21) = 16{\cdot}1L + 16{\cdot}1 \times 21.$$
$$86{\cdot}19 \times 19 = 16{\cdot}1L + 338{\cdot}1,$$
$$1637{\cdot}6 = 16{\cdot}1L + 338{\cdot}1,$$
$$16{\cdot}1L = 1299{\cdot}5,$$
$$L = \mathbf{80{\cdot}7\ cal.\ per\ gm.}$$

NOTE. *The latent heat of fusion of ice, as determined by accurate experiment, is* 79·7 *gm. cal. per gm.*

EXPT. 10. **Change of state.**

OBJECT. *To determine the latent heat of vaporisation of water at atmospheric pressure.*

APPARATUS. An evaporating flask, steam trap, a calorimeter, stirrer and thermometer (Fig. 7).

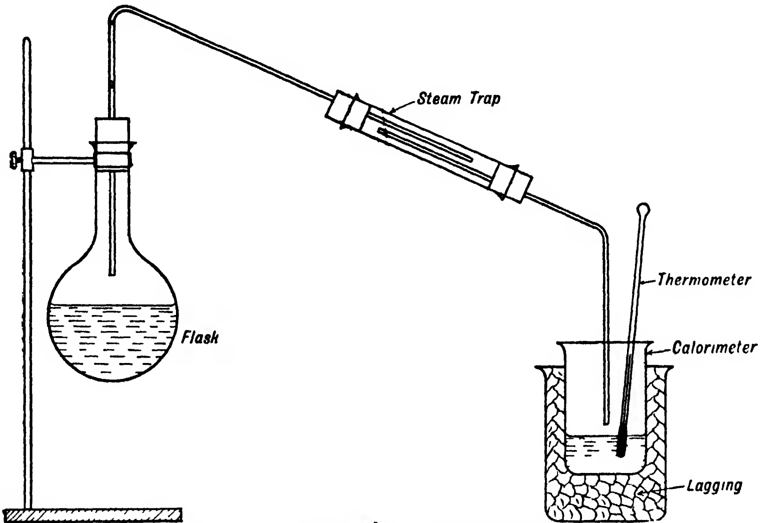


FIG. 7. Latent Heat of vaporisation.

METHOD OF PROCEDURE. Water is evaporated in the flask and the steam passed through the steam trap, where most of the condensed steam is retained. Thus the dry steam is passed into the calorimeter of cold water, where it is condensed and produces a rise of temperature. The following observations are taken : Weight of calorimeter, weight of calorimeter plus water before and after passage of steam, weight of water and the initial and final temperatures of the water. It is important to keep the water gently stirred during the passage of the steam.

OBSERVATIONS.

Weight of calorimeter $= 41{\cdot}4$ gm.

Water equivalent of calorimeter $= 41{\cdot}4 \times 0{\cdot}094 = 3{\cdot}89$ gm.

Weight of water + calorimeter $= 127{\cdot}6$ gm.

Weight of cold water $= 86{\cdot}2$ gm.

Weight of water + calorimeter + condensed steam	$= 130{\cdot}8$ gm.
Weight of condensed steam	$= \quad 3{\cdot}2$ gm.
Temperature of cold water	$= 17°$ C.
Final temperature of water	$= 38°$ C.
Temperature of steam	$= 100°$ C.

DERIVED RESULTS. The process of condensation of the steam gives to the cold water a quantity of heat represented by the loss of latent heat by the condensed steam. *Thus, the heat given to the water and the calorimeter is equal to the latent heat given up by the steam together with the sensible heat required to reduce the temperature of this condensed steam to the final temperature of the water.*

Heat given to calorimeter + water

$$= (86{\cdot}2 + 3{\cdot}89) \times (38 - 17) = 90{\cdot}09 \times 21 = 1892 \text{ cal.}$$

Let L be the latent heat of steam.

Then heat lost by steam

$$= \text{latent heat} + \text{heat lost by condensed steam}$$

$$= 3{\cdot}2L + 3{\cdot}2(100 - 38) = 3{\cdot}2L + 198{\cdot}4 \text{ cal.}$$

$$3{\cdot}2L + 198{\cdot}4 = 1892.$$

$$3{\cdot}2L = 1892 - 198{\cdot}4 = 1694.$$

$$L = \mathbf{529{\cdot}4 \text{ cal. per gm.}}$$

NOTE. *The value of the latent heat of vaporisation of water is, when determined by accurate experiment,* 539·44 *cal. per gm. The variation of the result obtained experimentally is due to the small losses caused by condensation of steam in its passage to the condenser and to loss due to radiation.*

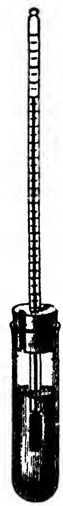


FIG. 8.
Expt. 11.

EXPT. 11. **Melting point from the cooling curve.**

OBJECT. *To find the melting point of naphthalene by examination of its cooling curve.*

APPARATUS. Take a small test tube and fit to it a cork carrying a thermometer. Groove the side of the cork so that the tube may not be airtight. Arrange in a suitable retort stand.

METHOD OF PROCEDURE. Melt in the test tube a quantity of paraffin wax or naphthalene ; then allow the wax to cool, recording the temperature at minute intervals until solidification has taken place. Plot a graph of temperature against time of cooling.

OBSERVATIONS.

Time in mins.	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Temp. ° Cen.	88	81	79	78	78	78	78	78	78	78	77	76	75	74

GRAPH AND ITS INTERPRETATION. The temperature falls until for some period there is a steady temperature reading. This is the melting temperature of the wax, and the constancy of temperature is produced by the latent heat of the cooling wax providing a com pensation for the ordinary loss of heat by cooling.

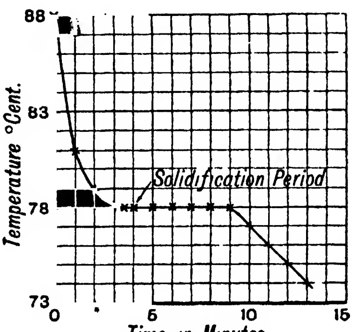


FIG. 9. Expt. 11.

NOTE. It must be remembered that these results are taken with an ordinary thermometer; under more accurate recording the solidification line would not be perfectly horizontal; in other words, the latent heat would not exactly compensate the loss of heat by cooling.

This experiment can be profitably performed in laboratories, where facilities exist for measuring higher temperatures, with molten lead, and the results indicate a similar behaviour in the case of metals. Where an alloy is used there will be two or more solidification lines indicating the melting points of the constituent metals. A change of volume also accompanies a change of state (p.81).

EXPT. 12. **Regelation.**

The freezing point of water varies according to the pressure at which freezing occurs. Thus when ice is subjected to pressure the melting point becomes lower and some of the ice melts. When the resulting free water comes under atmospheric conditions it freezes again, and the property is called **regelation.** The experiment described illustrates this process of regelation. Support a piece of ice with a ring of stout copper wire surrounding it. Add a weight to the

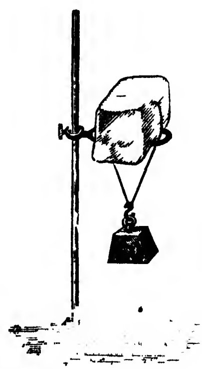


FIG. 10. **Experiment on regelation.**

copper ring, and leave the ice for some time. It will be found that the pressure exerted by the copper wire will melt the ice immediately under the wire, and the wire will cut slowly through until it is ultimately free of the ice. While this is in process the water, still at 0° C., released by fusion of the ice will again be at atmospheric pressure and have a freezing point of 0° C., therefore it will again freeze, and after the wire has cut through, the ice will be found to be still in one solid piece.

Example 1. *Some water is raised in temperature from* 15° *C. to* 100° *C. by blowing* 30 *lb. of steam at atmospheric pressure into it. If the latent heat of steam at this pressure is* 539·44 *C.H.U. per lb., calculate the weight of water heated.*

Let W = wt. of water.

Heat gained by water = heat lost by the steam.

$$W \times (100 - 15) \times 1 = 30 \times 539{\cdot}44.$$

$$W = \frac{30 \times 539{\cdot}44}{85} = \mathbf{190{\cdot}4\ lb.}$$

Example 2. *The latent heat of fusion of zinc at atmospheric pressure is* 26·6 *C.H.U. per lb. and its melting point is* 419·45° *C. How much of a block of zinc weighing* 40 *lb. at* 419·45° *C. could be melted by supplying* 1000 *C.H.U.? Neglect all losses.*

26·6 C.H.U. will melt 1 lb. of zinc.

$$1 \text{ C.H.U. will melt } \frac{1}{26{\cdot}6} \text{ lb. of zinc.}$$

$$\therefore\ 1000 \text{ C.H.U. will melt } \frac{1000}{26{\cdot}6} \text{ lb.} = \mathbf{37{\cdot}6\ lb.\ of\ zinc.}$$

Example 3. *If the latent heat of fusion of tin is* 14·4 *C.H.U. per lb. at atmospheric pressure, calculate the total heat per lb., the quantity of sensible and latent heat in* 1 *cwt. of molten tin at its melting point of* 232° *C. Assume the specific heat of tin has a mean value of* 0·055 *over the range* 0° *to* 232° *C. and measure the heat content above a datum level of* 0° *C.*

Total heat per lb. of tin $= 1 \times 0{\cdot}055 \times 232 + 14{\cdot}4 =$ **27·16 C.H.U.**

Sensible heat above 0° C. $= 112 \times 0{\cdot}055 \times 232 =$ **1429 C.H.U**

Latent heat $= 112 \times 14{\cdot}4 =$ **1613 C.H.U.**

Total heat reckoned from 0° C. = **3042 C.H.U.**

Example 4. *Find the final temperature of 100 gallons of cooling water, initially at 15° C., which has been used to condense 100 lb. of ammonia vapour at atmospheric pressure, if the latent heat of vaporisation of ammonia at this pressure is 341 gm. cal. per gm. The water and ammonia do not mix.*

$$341 \text{ gm. cal. per gm.} = \frac{341}{453 \cdot 6} \text{ lb. cal. per gm.,}$$

$$= \frac{341 \times 453 \cdot 6}{453 \cdot 6} \text{ lb. cal. per lb., since 1 lb.} = 453 \cdot 6 \text{ gm.}$$

$$= 341 \text{ lb. cal. per lb.}$$

∴ 100 lb. of ammonia vapour will give up 341×100 lb. cal. or C.H.U. to the cooling water.

$$\therefore \text{ rise of temperature} = \frac{34{,}100}{\text{wt. of water}} = \frac{34{,}100}{1000} = 34 \cdot 1° \text{ C.}$$

$$\text{Final temperature} = 15° + 34 \cdot 1° = 49 \cdot 1° \text{ C.}$$

Pressure. Many references have already been made to the word pressure in a general way. Pressure is a force, usually specified as acting on unit area, and the engineer is concerned with the measurement of the forces exerted by liquids and gases in different circumstances. In 1643 Torricelli tested his idea that air had weight by showing that the weight of the atmosphere exerted a pressure which could support a column of mercury. The height of this mercury column provided a means of measuring the magnitude of the atmos-

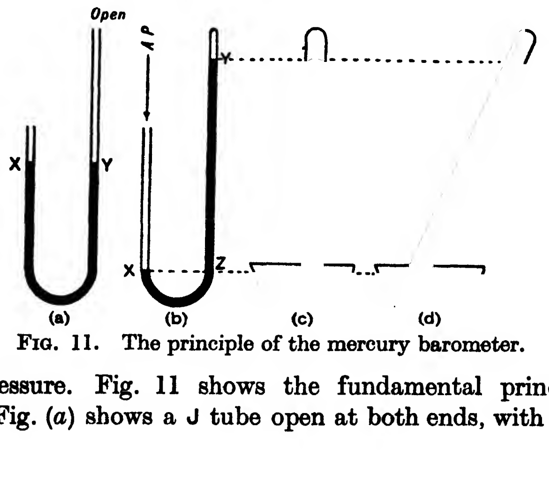


FIG. 11. The principle of the mercury barometer.

pheric pressure. Fig. 11 shows the fundamental principles involved. Fig. (*a*) shows a J tube open at both ends, with the levels

of mercury at X and Y the same, since the air pressure is the same on each surface. In Fig. 11 (*b*), the long arm is closed and its upper end freed from all air and vapour, except that of mercury. This upper portion is almost a vacuum, the vapour pressure on the surface Y being negligible at ordinary temperatures. The pressure on the surface X is that due to the air, and therefore the difference of level and pressure between X and Y represents the atmospheric pressure. If the cross-sectional area of the tube is 1 sq. in., then the weight of the column YZ represents the atmospheric pressure in lb. per sq. in. Standard pressure is that due to a column of 30 in. (or 760 mm.) of mercury at 0° C. under standard gravity. Thus standard pressure

$$= \text{height of column} \times \text{area} \times \text{wt. of 1 cu. in. of mercury}$$
$$= 30 \times 1 \times 0{\cdot}49 = 14{\cdot}7 \text{ lb. per sq. in.}$$

The height of the mercury column sustained by a given pressure is the same whatever the cross-section of the tube or the angle at which it is held (Fig. 11 (*c*) and (*d*)). It is customary to speak of the pressure of liquids and gases as equivalent to so many inches or millimetres of mercury. Atmospheric pressure, or the barometer reading, may be referred to as so many in. or mm. of mercury.

Fig. 12 shows diagrammatically how a mercury column (often called a **manometer**) could be employed to measure very low boiler pressures or flue draughts. The pressure on surface X must be the same as on a section at Z, therefore YZ registers the pressure inside the boiler. This pressure is called the **gauge pressure.** Since the pressure at Z is equal to atmospheric pressure plus that due to column of mercury YZ, then the actual pressure at X, which is termed the **absolute pressure** is equal to the atmospheric pressure plus the gauge pressure.

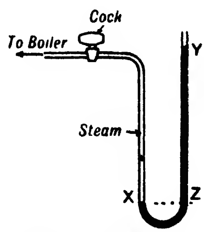


FIG. 12. Manometer tube.

Pressures below atmospheric have often to be employed. Instruments used for the measurement of pressure less than atmospheric are called **vacuum gauges.** A simple mercurial vacuum gauge is shown in Fig. 13, which shows a condenser pressure depressing the mercury column down to 25 in. Hence the absolute pressure in the condenser must be barometric pressure

minus vacuum gauge reading. Vacuum pressures are measured below atmospheric, so that if the barometer were 29 in. and the absolute pressure in the condenser 4 in., the condenser pressure would be referred to as a vacuum of 25 in. A modern condenser often produces a vacuum of nearly 29 in. with a barometer reading of 30 in. This means the absolute pressure (measured above zero pressure) must be just over 1 in. of mercury.

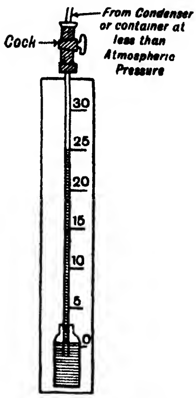


FIG. 13. Vacuum gauge.

NOTE.—A pressure of 1 in. of mercury $= 1 \times 13{\cdot}6$ or 13·6 in. of water, because mercury is 13·6 times as heavy as water.

Pressure gauges are instruments which do not employ columns of liquids for measuring pressures.

A large range of gauges are made to register blast and gas pressures up to 2 lb. per sq. in., and for recording hydraulic pressures of 12 tons per sq. in. For low pressures a diaphragm arrangement may be used, as with the aneroid barometer. These Schaffer gauges, which employ the diaphragm arrangement, will stand very rough usage. The deflection at the centre of a corrugated diaphragm is taken up through a link and pivoted toothed quadrant to a pinion which turns a pointer over a calibrated dial. These gauges, as well as those of the Bourdon type now to be described, may be used to indicate the pressure of steam, gas, water, ammonia, brine, petrol and oil.

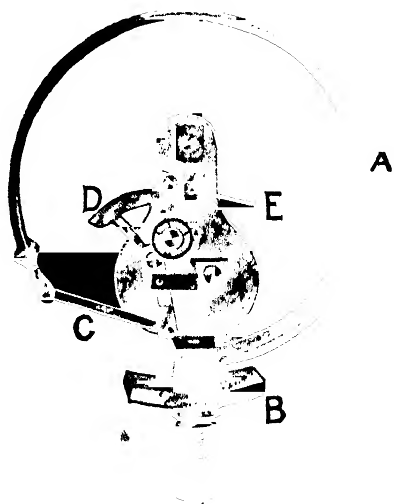


FIG. 14. Bourdon pressure gauge.

The **Bourdon pressure gauge** (Fig. 14) may be designed for high, low or vacuum pressure

readings. The mechanism is fitted in a brass case with provision for a graduated and calibrated dial to show the range of pressures to be measured. The pressure is actually measured by the movement of the free end of the curved tube, which is magnified by a toothed sector, and a pinion which carries the indicating needle. This curved tube is of flattened elliptical or D section. It is solid drawn, and made of special quality phosphor bronze for pressures up to 1800 lb. per sq. in., and of alloy steel for higher pressures or for corrosive fluids. A screwed joint connects one end of the tube to the source of pressure, while the free end is connected by a link, freely jointed, to the arm of the pivoted toothed sector. A return spring prevents "backlash" between the sector and the pinion. The admission of fluid under pressure tends to straighten the tube and as one end is fixed, the movement takes place at the free end. This movement drags the link C connected to the sector arm, and the sector D is compelled to rotate about its fulcrum. This movement is transmitted from the sector to the pinion, which, in turn, is coupled to the pointer or indicator above the dial. Thus the pressure is registered on the dial according to the amount of straightening of the curved tube.

EXPT. 13. **Dead weight test of a pressure gauge.**

OBJECT. *To calibrate a pressure gauge by comparison with a dead weight pressure on the fluid.*

APPARATUS. The apparatus (Fig. 15) consists of a cast steel cylinder A, fitted to a stand and bored to receive a hardened steel cylinder B. The hole in the cylinder B is carefully ground and lapped to fit a plunger C, the area of cross-section of which is $\frac{1}{8}$ sq. in., that is, 0·399 in. in diameter.

This plunger is cut away along the major portion of its length to a small bearing area of about $\frac{1}{100}$ in. in width (Fig. 15 (*a*)), thus reducing the bearing friction between the plunger and the cylinder. The top of the plunger is turned to a cone, and this cone supports carefully turned cast iron weights, of weight respectively $1\frac{1}{4}$, $2\frac{1}{2}$, $6\frac{1}{4}$, $12\frac{1}{2}$, 25, $37\frac{1}{2}$, 50 lb. with the plunger. The main cylinder A is bored and a union fitted at D, which connects to a standard E arranged to receive two, or more, pressure gauges. The end of this standard E is connected to a small hydraulic pump and intensifier in which good quality oil is employed.

METHOD OF PROCEDURE. The object of this experiment is to calibrate a pressure gauge to read pressures up to 400 lb. per square inch. The dial of the gauge is first given a coat of flat white paint and the circle marked in Indian ink. Next the needle is attached to mark zero gauge pressure or atmospheric pressure, and the gauge screwed into position in the standard E. Other gauges may be fitted to the standard, or alternatively the spare unions may be blanked. Place the $1\frac{1}{4}$ lb. weight upon the cone of the plunger, use the pump to charge the intensifier, and then intensify until the weight is just floating freely with the plunger on the oil. The weight should now be given a circular or rotary motion to minimise friction between

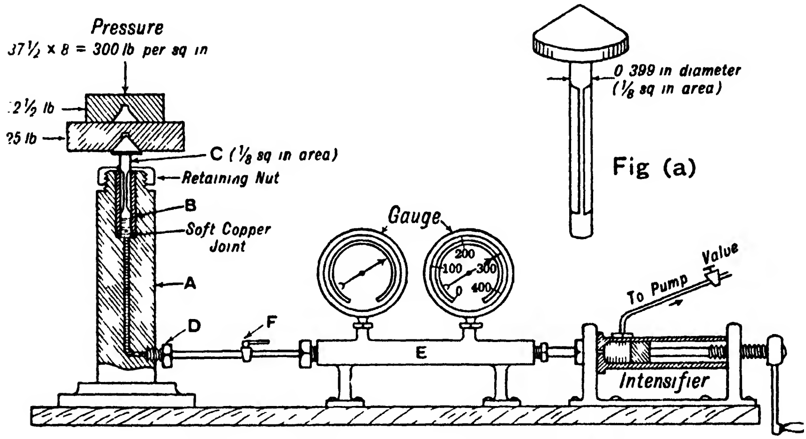


FIG. 15. Calibration of a pressure gauge.

the plunger and cylinder. The oil throughout the circuit, that is under the plunger and in the gauge, will be subjected to a pressure of $1\frac{1}{4}$ lb. on $\frac{1}{8}$ sq. in. area, that is 10 lb. per sq. in., and the face of the gauge may be marked in pencil for the needle reading at this pressure. Replace the $1\frac{1}{4}$ lb. weight by the $2\frac{1}{2}$ lb., first relieving the pressure, and repeat the experiment, thus giving a gauge pressure of $2\frac{1}{2} \times 8 = 20$ lb. per sq. in. Repeat with the remaining cast iron weights up to 50 lb., which will give a gauge pressure of $50 \times 8 = 400$ lb. per sq. in., marking the needle reading for each pressure. The dial may now be removed and the lines carefully drawn in and the printing added, thus calibrating the gauge. This apparatus may be used to calibrate a gauge against one which is known to be correct by closing the cock F and attaching the two gauges to the standard E.

NOTE. It is important that the oil used should be of a mobile character and free from sediment and grit. A good quality sperm oil has been found to give the best results, but a light machine oil can be used, providing it is filtered before service to the intensifier.

Recording chronometer pressure gauges are used to obtain a record of the variation of pressure (or temperature) over a period or shift. The gauge is arranged to leave a permanent record by inking, or marking, the paper on a revolving drum that turns at a prearranged speed, and the markings indicate to the engineer the performance of the boiler or machine during his absence. This method is particularly important in work on high explosives, where access to the operation may be accompanied by risk.

Laws of chemical combination. The calculations for the minimum quantity of air required by a fuel for complete combustion (p. 3) are made possible because of the following laws of chemical combination :

(1) *when elements combine to form a new substance they do so in definite proportions ;*

(2) *the sum of the weights of the separate elements is equal to the total weight of the new substance formed.*

Law (2) is another interpretation of the law of the conservation of matter, which states that matter can neither be created nor destroyed.

Every element is considered to be composed of minute chemically indivisible particles called **atoms.** Atoms of the same or different elements are associated in pairs or larger groups to form stable units called **molecules.** The atoms of an element are characteristic of that element alone ; they differ from element to element. The chemist regards a molecule as the smallest part of a substance that can exist by itself, and the molecule may contain atoms of different elements. Hydrogen is the lightest known substance, and by taking the weight of an atom of hydrogen as unity it has been possible to obtain the *relative* atomic and molecular weights of other substances. The actual weights would, of course, be very minute.

The **atomic weight** of an element is the number of times an atom of that element is heavier than an atom of hydrogen.

The **molecular weight** of a substance is the number of times a molecule of the substance is heavier than an atom of hydrogen.

Elements and compounds are represented by symbols, and usually the symbol for an atom consists of its initial letter. A suffix is added to denote the number of atoms of any given element, while a coefficient is used to indicate the number of molecules. For example, $3H_2O$ denotes 3 molecules of water (H_2O), each consisting of 2 atoms of hydrogen (H_2) and one of oxygen (O). H_2O is the chemical formula indicating the composition of water.

The following table contains the chief elements and compounds concerned in combustion and information concerning them for combustion calculations.

Element * or compound	Symbol	Atomic weight	Molecular weight	Calorific value per lb. Gross B.Th.U.	Net B.Th.U.	Gross C.H.U.
*Hydrogen	H_2	1	2	61,750	57,790	34,300
*Oxygen	O_2	16	32	—	—	—
*Nitrogen	N_2	14	28	—	—	—
*Carbon (to carbon monoxide)	C	12	—	4,410	4,410	2,450
(to carbon dioxide)				14,650	14,650	8,140
*Sulphur	S	32	—	3,960	3,960	2,200
Carbon monoxide	CO	—	28	10,240	10,240	5,690
Marsh gas or methane	CH_4	—	16	23,830	21,450	13,240
Ethylene	C_2H_4	—	28	—	—	—
Acetylene	C_2H_2	—	26	21,460	20,700	11,920
Sulphur dioxide	SO_2	—	64	—	—	—
Carbon dioxide	CO_2	—	44	—	—	—
Water or steam	H_2O	—	18	—	—	—

Equations are also employed to represent the chemical laws quoted above, as they show in a concise form the complete nature of a particular form of chemical action or reaction.

Equations of Combustion.

The equation representing the combustion of hydrogen is as follows :

2 molecules of hydrogen added to one of oxygen produces 2 molecules of water :

$$2H_2 \quad + \quad O_2 \quad = \quad 2H_2O.$$

Therefore $$2 \times 2 \quad + \quad 32 \quad = \quad 36,$$

where 2 and 32 are the molecular weights of hydrogen and oxygen. See Table, p. 36.

Dividing through by 4,

1 lb. of hydrogen needs 8 lb. of oxygen to produce 9 lb. of steam or water.

For the complete combustion of carbon to carbon dioxide (CO_2),

$$C \quad + \quad O_2 \quad = \quad CO_2$$

$$12 \quad + \quad 32 \quad = \quad 44$$ where 12 = atomic weight of carbon.

Dividing by 12,

1 lb. of carbon needs $2\frac{2}{3}$ lb. of oxygen to produce $3\frac{2}{3}$ lb. of carbon dioxide.

If the combustion is incomplete, due to an insufficient supply of oxygen, the equation is

$$2C \quad + \quad O_2 \quad = \quad 2CO$$

$$2 \times 12 \quad + \quad 32 \quad = \quad 56$$

Dividing by 24,

1 lb. of carbon needs $1\frac{1}{3}$ lb. of oxygen to produce $2\frac{1}{3}$ lb. of carbon monoxide.

There is, of course, considerable waste of heat if carbon monoxide is allowed to escape unburnt.

The equation for the combustion of sulphur (S) is :

$$S \quad + \quad O_2 \quad = \quad SO_2$$

$$32 \quad + \quad 32 \quad = \quad 64$$

Dividing by 32,

1 lb. of sulphur needs 1 lb. of oxygen to produce 2 lb. of sulphur dioxide.

The power which atoms possess of combining with a definite number of other atoms to form a new substance is called **valency.** Numerically, the valency of an element can be expressed by the number of hydrogen atoms which it can combine with or replace. Thus oxygen is said to have a valency of two, because it always combines with two atoms of hydrogen to form water, and carbon has a valency of four, because it replaces four atoms of hydrogen. For example, if the carbon atom in carbon dioxide (CO_2) were replaced by four hydrogen atoms, water ($2H_2O$) would be formed.

Example. *The chemical composition of a sample of coke is 85·8% C, 0·6% H, 1·2% N, 1·9% S, 0·6% O and 9·9% ash. Calculate the minimum quantity of air required per lb. of coke. If 50% of excess air is supplied, find, assuming complete combustion, the weights of the respective flue gases per lb. of coke.*

In 1 lb. of coke there will be 0·858 lb. of C, 0·006 lb. of H, 0·012 lb. of N, 0·019 lb. of S, 0·006 lb. of O, and 0·099 lb. ash.

0·858 lb. of C needs $0{\cdot}858 \times 2\frac{2}{3}$ lb. of oxygen $= 2{\cdot}288$ lb.
0·006 lb. of H needs $0{\cdot}006 \times 8$ lb. of oxygen $= 0{\cdot}048$ lb.
0·019 lb. of S needs $0{\cdot}019 \times 1$ lb. of oxygen $= 0{\cdot}019$ lb.

Total $= 2{\cdot}355$ lb.
Amount of oxygen in fuel $= 0{\cdot}006$ lb.
Oxygen needed $= 2{\cdot}349$ lb.

This wt. of oxygen is contained in $2{\cdot}349 \times \frac{100}{23}$ lb. of air $=$ **10·21 lb. of air.**

If 50% excess air is supplied, $1{\cdot}5 \times 10{\cdot}21 = 15{\cdot}31$ lb. is needed.
This will contain $0{\cdot}77 \times 15{\cdot}31 = 11{\cdot}79$ lb. of nitrogen
and $0{\cdot}23 \times 15{\cdot}31 = 3{\cdot}52$ lb. of oxygen.

Products of combustion from 1 lb. of coke:

Wt. of carbon dioxide	$= 0{\cdot}858$ of C $+ 2{\cdot}288$ of O	= **3·146 lb.**
Wt. of steam (H_2O)	$= 0{\cdot}006$ of H $+ 0{\cdot}048$ of O	= **0·054 lb.**
Wt. of sulphur dioxide	$= 0{\cdot}019$ of S $+ 0{\cdot}019$ of O	= **0·038 lb.**
Wt. of nitrogen	$= 0{\cdot}012$ in fuel $+ 11{\cdot}79$ in air	= **11·802 lb.**
Wt. of oxygen	$= 3{\cdot}52$ supplied $- 2{\cdot}349$ used	= **1·171 lb.**
Wt. of ash		= **0·099 lb.**
	Total	= **16·310 lb.**

Calorific value and its measurement. The calorific value (C.V.) is the definite amount of heat generated or given out when unit

quantity of a fuel is completely burnt. The heat units usually employed are the B.Th.U., C.H.U., and the gram calorie. Also the units of quantity are generally the lb. for solid fuels, either the lb., litre or gallon for liquid fuels, and either the cubic ft. or lb. for gaseous fuels. With gases, if the unit of quantity is the cubic foot, it is most important to specify the temperature and pressure of the gas. The pressure generally stated is that of 30 in. of mercury, and the temperature sometimes 0° C. and sometimes 60° F. ($15\frac{5}{9}$° C.).

Examples. The calorific value of coal gas is 500 B.Th U. per cu. ft. at 60° F. and 30 in. of mercury.

The C.V. of hydrogen is 34,300 C.H.U. per lb.

Charcoal has a C.V. of 13,000 B.Th U. per lb.

At N T P. (normal temperature 0° C. and pressure 14·7 lb. per sq. in., or 30 in of mercury) the C.V. of water gas is 308 B Th.U. per cu. ft.

The temperature to which the calorific value or heat evolved can raise the products of combustion with the minimum amount of air (*i.e.* without excess air) is also important from a practical point of view. This temperature is called the **calorific intensity.** If impurities are present, both the calorific value and the calorific intensity are affected.

Determination of calorific value from the chemical composition. The calorific value may be determined *approximately* if the chemical composition of the fuel is known. This is done by multiplying the weight of each constituent or element in 1 lb. of fuel by its calorific value and adding the results.

It is generally assumed that if hydrogen and oxygen are both present in a fuel the oxygen has already combined chemically with one-eighth of its weight of hydrogen to form water. This fraction must be deducted from the hydrogen content in making the calculation. Suppose C, H and S represent respectively the weights of the combustibles carbon, hydrogen and sulphur and O the weight of oxygen per lb. of fuel. From table, p. 36,

1 lb. of C produces 14,650 B.Th.U.,

1 lb. of H produces 61,750 B.Th.U. (gross),

1 lb. of S produces 3,960 B.Th.U.

Hence,

$$\text{Total or gross C.V.} = 14{,}650C + 61{,}750\left(H - \frac{O}{8}\right) + 3{,}960S \text{ in B.Th.U. per lb.,}$$

or
$$8{,}140C + 34{,}300\left(H - \frac{O}{8}\right) + 2{,}200S \text{ in C.H.U. per lb.}$$

Example 1. *Determine the calorific value of 1 lb. of coal containing 77% carbon, 5% hydrogen, 7% oxygen, 1·5% nitrogen, 1·5% sulphur and 8% ash.*

$$\begin{aligned}\text{Gross value} &= 14{,}650C + 61{,}750\left(H - \frac{O}{8}\right) + 3{,}960S \\ &= 14{,}650 \times 0{\cdot}77 + 61{,}750\left(0{\cdot}05 - \frac{0{\cdot}07}{8}\right) + 3960 \times 0{\cdot}015. \\ &= 11280{\cdot}5 \quad + 2547 \quad + 59{\cdot}4 \\ &= \mathbf{13{,}887\ B.Th.U.}\ \text{or}\ \tfrac{5}{9} \times 13{,}887 = \mathbf{7715\ C.H.U.\ per\ lb.}\end{aligned}$$

Example 2. *Cellulose, which is the chief constituent, or forms the bulk of, plant structure, has a chemical composition of* 44% C, 6·2% *of H and* 49·4% *of O. Calculate its approximate calorific value.*

$$\begin{aligned}\text{Gross C.V.} &= 14{,}650 \times 0{\cdot}44 + 61{,}750\left(0{\cdot}062 - \frac{0{\cdot}494}{8}\right) \\ &= 6446 \quad + \quad 15 \\ &= \mathbf{6461\ B.Th.U.\ per\ lb.}\end{aligned}$$

Gross and net calorific value. It must be remembered that the useful heat which can be obtained from a fuel is less than its calorific value. In practice, combustion is imperfect, and heat is carried away and lost in the flue gases, clinkers and ash. It is true that some of the heat energy in the flue gases is usefully employed, with the aid of a chimney, in creating the draught of air necessary for efficient combustion. Furthermore, when fuel containing hydrogen is burnt, steam is produced, and the latent and sensible heat contained in this steam is usually lost up the chimney. This is because the temperature of the surrounding hot products of combustion is too high to allow of condensation of the steam. When this latent heat and the sensible heat above ordinary room temperature (say about 15° C. or 60° F.) is deducted from the total heat produced, that is, the **gross** or **higher calorific value** as it is called a quantity

known as the **net or lower calorific value** is obtained. Hence the net calorific value is the maximum value usually obtainable under working conditions.

Then

$$\text{net C.V.} = \text{gross C.V.} - \text{wt. of steam} \times [L_a + (h_{100} - h_{15})].$$

L_a = latent heat of steam at a pressure of 14·7 lb. per sq. in.

h_{100} = sensible heat contained in water at 100° C. above datum 0° C.

h_{15} = sensible heat contained in water at 15° C. above datum 0° C.

Corresponding temperatures on the Fahrenheit scale are 212° F. and 60° F.

Efficiency of combustion. This may be defined as the ratio

$$\frac{\text{heat usefully employed}}{\text{heat supplied or evolved}} \text{ or } = \frac{\text{heat output}}{\text{heat input}}.$$

Thus the efficiency of combustion can be reckoned in a similar way to that of any other operation. The same ratio may be regarded as giving the **thermal efficiency** of a boiler or engine.

Example. *The chemical composition of an average sample of lignite is 67% C, 5·1% H, 19·5% O, 1·1% N, 1% S, and 6·3% ash. Calculate its gross and net calorific values in B.Th.U. and also in C.H.U. per lb.*

$$\text{Gross C.V.} = 14{,}650 \times 0{\cdot}67 + 61{,}750\left(0{\cdot}051 - \frac{0{\cdot}195}{8}\right) + 3960 \times 0{\cdot}01.$$

$$= 9815{\cdot}5 \qquad + 1644{\cdot}1 \qquad + 39{\cdot}6$$

$$= \textbf{11,499 B.Th.U. or 6388 C.H.U. per lb.}$$

Wt. of steam formed per lb. of fuel $= 0{\cdot}051 \times 9 = 0{\cdot}459$ lb.

Heat in steam per lb. of coal = Wt. of steam $\times [L_a + (h_{212} - h_{60})]$ B.Th.U.

$= 0{\cdot}459 \times [970{\cdot}7 + (212 - 60)]$ B.Th.U.

$= 0{\cdot}459 \times 1122{\cdot}7 = 515{\cdot}2$ B.Th.U.

∴ Net calorific value $= 11{,}499 - 515{\cdot}2 =$ **10,984 B.Th.U. per lb.**

= **6,102 C.H.U. per lb.**

The above method gives approximate results, but the most satisfactory means of obtaining the calorific value of a fuel is by actual experiment. See Expt. 14.

The apparatus used to find the heat energy released by the combustion of fuel is called a **fuel calorimeter**, because it measures the calorific value of the fuel.

Calorific value of solid and liquid fuels.

EXPT. 14. OBJECT. To find the calorific value of a sample of coal.

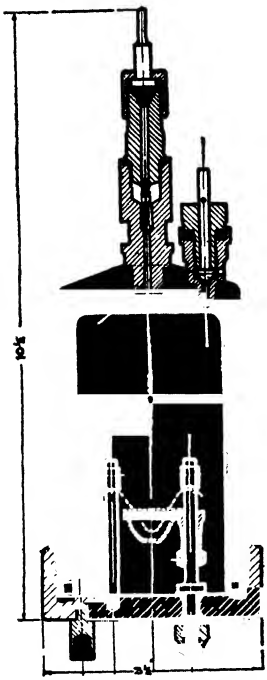


FIG. 16. Section through Schole's calorimeter. (*Messrs. G. Cussons, Ltd.*)

APPARATUS. The calorimeter shown in Fig. 16, and developed and patented by Prof. Scholes, is made mainly of acid-resisting stainless steel, which is able to withstand heat, pressure and corrosion. It can be assembled and rendered gas-tight without a spanner in a few seconds, by merely screwing the cover into the base. The design is simple, and the body of the bomb and the cover which holds the crucible and forms the base are both machined from the solid. The head of the body of the bomb carries the non-return inlet oxygen valve on its main axis and the outlet screw-down valve, for the discharge of the gaseous products of combustion, to one side. A gas-tight joint is made by means of a rubber ring which fits into a slight recess in the base, and this rubber ring is protected by being partly covered by the inner face of the body of the bomb. The joint is made good by the high pressure of the oxygen in the calorimeter forcing the rubber against the metal seats. A cradle, carried by the ignition rod on the right, supports the crucible, which in turn holds the sample of fuel. The ignition wire, made of platinum or nichrome wire of 0·004 in. diameter, dips into the crucible between the two ignition rods. One of the latter is screwed into the base, while the other passes through but is insulated from it and is supplied with a spring foot to form a good contact. The crucible may be made of silica ware, fire clay, platinum or porcelain.

METHOD OF PROCEDURE. The crucible is weighed and about a gram of finely powdered and dried coal (or about $\frac{3}{4}$ gm. of oil fuel)

placed in it, and it is again weighed. The difference will give the weight of the fuel. Then the crucible is placed in its cradle and the ignition wire adjusted to give good contact. With light oils and petrol the crucible is usually supported by a heavier metal crucible to prevent it being upset by the rapidity of the combustion, and the difference of pressure set up. 15 cubic centimetres of water are placed in the base of the bomb to absorb any nitric or sulphuric acid which may be formed, and then the calorimeter is assembled. Connection is then made to an oxygen cylinder and the bomb charged to a pressure of about 25 atmospheres (367·5 lb. per sq. in.). The bomb is submerged in a known weight of water (about $\frac{1}{2}$ gallon) contained in a large copper calorimeter, which is itself placed within and insulated from a second larger calorimeter to lessen losses by radiation of heat. Papier mâché covers are also employed for the same purpose. The standard research outfit is also provided with a third outside covering and an automatic stirring gear. The water should be to a degree or two below room temperature, and the final temperature after combustion the same amount above. This also tends to produce a more accurate result, as the average temperature conditions for the experiment are the same as for the room. The fuel can now be ignited by closing the circuit and fusing the wire, and the water is gently stirred to facilitate uniform heat absorption. The maximum temperature reached is carefully noted.

Since the apparatus, as well as the water, will be raised in temperature by the combustion of the fuel, it is necessary to find its **water value** or **water equivalent.** This is the amount of water which would require the same amount of heat as the apparatus to raise its temperature 1°. To find the water value of the bomb, copper calorimeter, thermometer and stirring rod, place a known weight W_1 of hot water at temperature $t_1°$ in the copper calorimeter which is contained in its outer covering. About $\frac{1}{2}$ gallon of water is necessary to submerge the bomb. The final temperature $t_2°$ of the water after a uniform temperature has been reached must be carefully noted. Then, assuming that no heat energy has been lost, the heat lost by the water is equal to the heat gained by the calorimeter, etc. Suppose the temperature of the room and apparatus is t_3 at first.

Mass × fall in temp. × specific heat = water equivalent × rise of temperature.

$$W_1 \times (t_1 - t_2) \times 1 = \text{water value} \times (t_2 - t_3).$$

$$\text{Water value} = \frac{W_1(t_1 - t_2)}{(t_2 - t_3)}.$$

Another common method of finding the water value is to measure the quantity of heat generated when a certain weight of fuel of known calorific value is burnt. By subtracting the heat given to the water by the known heat generated by the fuel and dividing by the temperature rise, the water equivalent can be found.

OBSERVATIONS. Fuel tested, South Wales anthracite.

Wt. of sample + crucible	=	3·09 gm.
Wt. of crucible	=	2·12 gm.
Wt. of fuel by difference	=	0·97 gm.
Temperature of room	=	14·1° C.
Wt. of water	=	2253 gm.
Water value of apparatus	=	438 gm.
Equivalent wt. of water	=	2691 gm.
Initial temp. of water	=	12·72° C.
Final temp. of water	=	15·65° C.
Rise of temp.	=	2·93° C.

Heat absorbed by water and apparatus

$$= \text{mass} \times \text{rise in temp.} \times \text{specific heat}$$
$$= 2691 \times 2{\cdot}93 \times 1$$
$$= 7885 \text{ calories.}$$

$$\text{Approx. calorific value} = \frac{\text{calories to water}}{\text{mass of fuel}}$$
$$= \frac{7885}{0{\cdot}97} = 8128 \text{ calories per gram}$$

= 14,630 B.Th.U. per lb.

= 8128 C.H.U. per lb.

The above set of observations and calculations will show how the calorific value can be obtained approximately. In more accurate work corrections are made for losses by radiation.

Calorific value of a gaseous fuel. Boys' calorimeter is shown in Fig. 17. The volume of gas used is measured by a gas meter, specially designed for the purpose and reading to $\frac{1}{1200}$ of a cubic foot. The gas then passes through a pressure regulator to the jets or burners in the gas calorimeter, in order to ensure an even flow of gas and steady combustion. Apparatus must also be provided for supplying a constant head and steady flow of cooling water and for measuring

its volume. The **principle of contra-flow** adopted, in which the water flows in the opposite direction to the hot products of combustion, should be specially noted. The pipes through which the cooling water flows are provided with fins or gills to supply as large a cooling surface as possible to the hot gases flowing on the outside. Before any final observations are made the apparatus must have been in use for upwards of half an hour to make sure the conditions of the experiment are steady. Then the quantity of water W lb. flowing while $\frac{1}{3}$ of a cubic foot of gas is burnt, and the rise of temperature $t°$ F. of the water, must be carefully noted. The gas and barometric pressures and gas temperature must also be obtained, as it is necessary to standardise the pressure and temperature of the gas owing to its great expansibility. The volume N cu. ft. which this $\frac{1}{3}$ cu. ft. would occupy at standard pressure (30 in. or 760 mm.) of mercury and 60° F. is then found by using the characteristic or gas equation, namely $PV = RT$ (see p. 71). Sometimes 32° F. is taken.

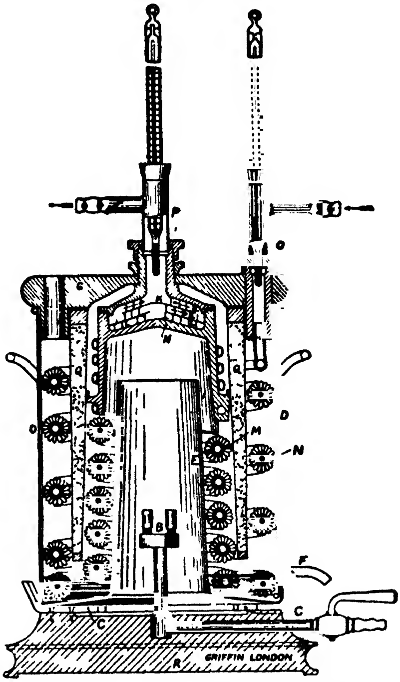


FIG. 17. Boys' gas calorimeter.

Then,

$$N \times \text{calorific value (C.V.)} = W \times t,$$

or

$$\text{C.V.} = \frac{W \times t}{N} \text{ B.Th.U. per standard cu. ft.}$$

This is called the **gross calorific value** of the gas, because it includes the latent heat and sensible heat above 60° F. of the steam produced by the combination of hydrogen in the gas. Normally this steam escapes into the flues and its heat is lost. As mentioned on p. 40, when this heat is deducted from the gross value, the **net calorific value** is obtained.

Avogadro's Law. *Equal volumes of gases at the same temperature and pressure contain the same number of molecules.* In other words, the molecules of every gas have the same volume at the same temperature and pressure. This law is very important, as it allows of (*a*) the density of any gas being determined when that of hydrogen is known, (*b*) the calculation of the volume of air required for combustion per cubic ft. of gaseous fuel.

The approximate composition of air by volume is 21% oxygen and 79% nitrogen.

A weight of gas in grams equal to its molecular weight is called a **mol.**

Example 1. *Find the densities of oxygen and nitrogen at normal temperature and pressure (N.T.P.) i.e. at 0° C. and 76 cm. of mercury.*

Density of hydrogen is 0·00559 lb. per cu. ft. at N.T.P.

Density of any other gas

$$=\frac{\text{molecular wt. of gas}}{\text{molecular wt. of hydrogen}}\times 0{\cdot}00559 \text{ lb. per cu. ft.}$$

Density of oxygen $=\frac{32}{2}\times 0{\cdot}00559=$ **0·08944 lb. per cu. ft.**

Density of nitrogen $=\frac{28}{2}\times 0{\cdot}00559=$ **0·07826 lb. per cu. ft.**

Example 2. *Find the volume of 1 lb. of carbon dioxide at N.T.P.*

Molecular weight of $CO_2 = 44$.

Molecular weight of $H_2 = 2$.

Density of CO_2 $=\frac{44}{2}\times 0{\cdot}00559 = 0{\cdot}12298$ lb. per cu. ft.

Vol. of 1 lb. $=\frac{1}{0{\cdot}12298}$ cu. ft. $=$ **8·131 cu. ft. at N.T.P.**

Example 3. *Determine the quantity of oxygen necessary to burn completely a cubic ft. of acetylene (C_2H_2). State the volumes of the various gaseous products produced by combustion.*

Combustion equation: $2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$.

$$\begin{pmatrix}\text{2 molecules}\\ \text{of}\\ \text{acetylene}\end{pmatrix}+\begin{pmatrix}\text{5 molecules}\\ \text{of}\\ \text{oxygen}\end{pmatrix}=\begin{pmatrix}\text{4 molecules}\\ \text{of}\\ \text{carbon dioxide}\end{pmatrix}+\begin{pmatrix}\text{2 molecules}\\ \text{of}\\ \text{steam.}\end{pmatrix}$$

Since the molecules of *every* gas have the same volume at the same temperature and pressure, then the volume of the gases will be proportional to the number of molecules.

$$\begin{matrix}\text{2 cu. ft. of}\\ \text{acetylene}\end{matrix}+\begin{matrix}\text{5 cu. ft. of}\\ \text{oxygen}\end{matrix}=\begin{matrix}\text{4 cu. ft. of}\\ \text{carbon dioxide}\end{matrix}+\begin{matrix}\text{2 cu. ft. of}\\ \text{steam.}\end{matrix}$$

$\therefore$ **$2\frac{1}{2}$ cu. ft. of oxygen will be required and 2 cu. ft. of carbon dioxide and 1 cu. ft. of steam will be produced.**

Example 4. *Find the minimum amount of air for the complete combustion of 1 cu. ft. of carbon monoxide at N.T.P. What is the percentage reduction in volume of the products of combustion with this least amount of air?*

Combustion equation, $2CO + O_2 = 2CO_2$.

2 molecules + 1 molecule = 2 molecules

By Avogadro's Law

$$\begin{pmatrix}\text{2 cu. ft. of}\\ \text{carbon monoxide}\end{pmatrix} + \begin{pmatrix}\text{1 cu. ft. of}\\ \text{oxygen}\end{pmatrix} = \begin{pmatrix}\text{2 cu. ft. of}\\ \text{carbon dioxide.}\end{pmatrix}$$

Dividing by 2, 1 cu. ft. + $\frac{1}{2}$ cu. ft. = 1 cu. ft.

$\therefore$ 1 cu. ft. of carbon monoxide requires $\frac{1}{2}$ cu. ft. of oxygen, both gases being at the same temperature and pressure.

At N.T.P., $\frac{1}{2}$ cu. ft. of oxygen is contained in $\frac{100}{21} \times \frac{1}{2} = 2{\cdot}381$ cu. ft. of air at N.T.P.

1 cu. ft. of CO + 2·381 cu. ft. of air becomes after combustion 1 cu. ft. of CO_2 + 1·881 cu. ft. of nitrogen.

That is, 3·381 cu. ft. becomes 2·881 cu. ft. after combustion.

$\therefore$ Reduction in 3·381 cu. ft. is 0·5 cu. ft. or $\frac{0{\cdot}5}{3{\cdot}381} \times 100\% = 14{\cdot}8\%$.

Example 5. *The temperature of a gas-fired furnace used for melting aluminium is 800° C., and 2·8 cubic ft. of gas are being burnt per lb. of aluminium melted. Calculate the efficiency of the furnace at 800 C. Take the melting point of aluminium as 657° C., the specific heat over the range 0° to 657° C. as 0·24, and the latent heat of fusion as 93. C.V. of gas 500 B.Th.U. per cu. ft. as burnt.*

Heat necessary to melt 1 lb. of aluminium above 0° C. datum in

C.H.U. $= 1 \times 657 \times 0{\cdot}24$ (sensible heat) + 93 (latent heat)

$= 157{\cdot}7 + 93 = 250{\cdot}7$ C.H.U.

Heat supplied $= 2{\cdot}8 \times 500$ B.Th.U. $= 1400$ B.Th.U. $= 778$ C.H.U.

Efficiency $= \frac{\text{output}}{\text{input}} \times 100 = \frac{250{\cdot}7}{778} \times 100 = 32{\cdot}2\%$.

Conversion of energy. The conversion of mechanical energy into heat energy and the reverse process are particular cases which illustrate the principle of Conservation of Energy which states that energy can neither be created nor destroyed. From the earliest times fires have been kindled by the rapid transference of mechanical into heat energy, but Dr. Joule of Manchester was the first to show that the

same quantity of mechanical work is always necessary to produce the unit of heat energy. The apparatus he used is shown in Fig. 18. The energy of the falling weights rotated the axle *f* and a system of paddles in the calorimeter AB. This calorimeter contained fixed vanes, and was filled with a known mass of water. The action of the moving and fixed vanes on the water and the churning action

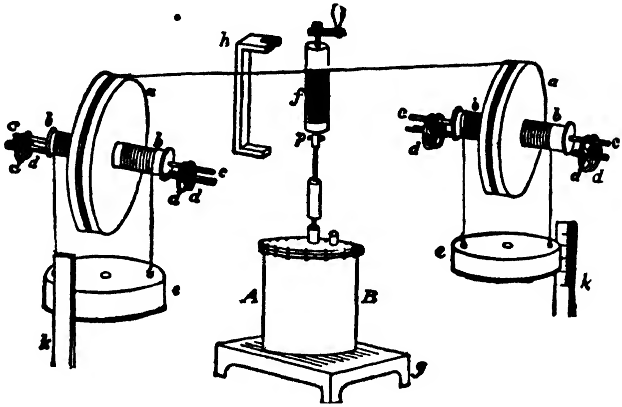


FIG. 18. Joule's apparatus.

set up converted the kinetic energy of the axle into heat energy. The rise of temperature of the water was recorded. Refinements in the apparatus were made to ensure accuracy as far as was possible. Thus the converted kinetic energy of the falling weights was equated to the heat received by the water. **Joule's equivalent** was given as 772 ft. lb. per B.Th.U. More accurate methods have since been devised for obtaining the value of Joule's equivalent, and now 778 is the figure generally adopted in Great Britain. Note that

$$778 \times \frac{9}{5} = 1400 \text{ ft. lb.} = 1 \text{ C.H.U.}$$

EXPT. 15. **Modified form of Callendar's apparatus.**

OBJECT. *To obtain a value for the mechanical equivalent of heat.*

APPARATUS. This apparatus (Fig. 19) is a modified form of Callendar's apparatus, and consists of a brass drum, to contain a definite quantity of water, mounted on a ball-bearing spindle and rotated by means of a hand wheel. The drum is fitted with a ribbon type of brake, the ends of which can be loaded after the manner of

the rope dynamometer (Chap. IV, p. 202) to produce the braking torque on the drum. The handwheel can be rotated at such a speed that the brake load is kept floating and a steady reading is given to the spring balance. A cyclometer type of revolution counter is fitted to the frame, and temperature rises are taken from the reading of a bent thermometer.

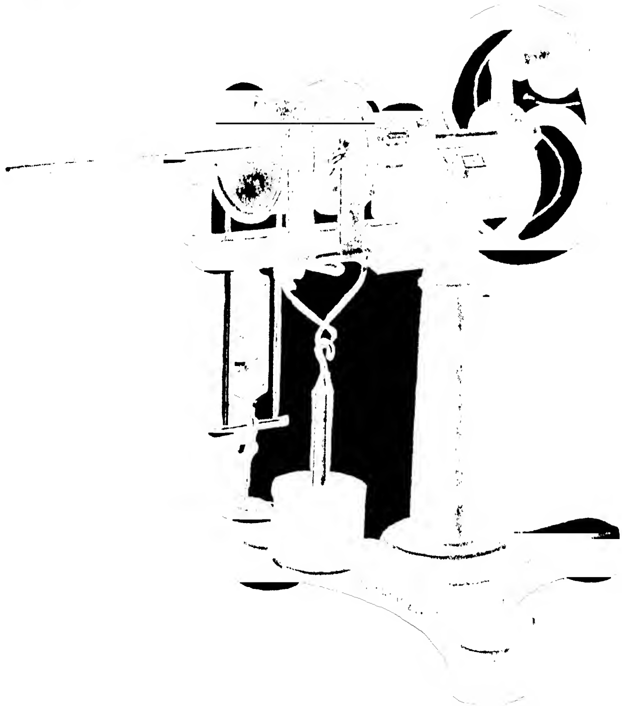


FIG. 19. Callendar's apparatus. (*Messrs. P. Harris & Co., Ltd.*)

METHOD OF PROCEDURE. Take the following measurements, which provide the constant quantities in the experiment. (*a*) Diameter of the drum, (*b*) weight of the drum, (*c*) water equivalent of the drum, using a specific heat value of 0·092 for brass. Fill the drum with cold water and determine the weight of water, replace the drum and note the temperature of the water. Add weights to the brake until a normal rotation of the handle and wheel will maintain a steady reading of the spring balance, and note the

initial counter reading. Turn the wheel steadily for about 400 revolutions, and note the rise of temperature produced in the drum by the absorption of the mechanical energy at the brake and its conversion to heat energy in the drum. The mechanical equivalent of heat may then be calculated by equating the work done at the brake to the heat given to the water and drum.

OBSERVATIONS.

Diameter of drum $= 3$ in. $= 0{\cdot}25$ ft.
Weight of drum $= 0{\cdot}51$ lb.
Specific heat of brass $= 0{\cdot}092$.
Water equivalent of drum $= 0{\cdot}0469$ lb.
Weight of water $= 0{\cdot}133$ lb.
$W =$ weight of water + water equivalent $= 0{\cdot}133 + 0{\cdot}0469$
$= 0{\cdot}1799$ lb.
$L =$ load on hanger $= 2{\cdot}0$ lb.
$S =$ spring balance reading $= 0{\cdot}2$ lb.
Initial reading of counter $= 0142$.
Final reading of counter $= 0510$.
Number of revolutions $= 368$ revs.
$t =$ initial temperature of water $= 19°$ C.
$T =$ final temperature of water $= 21{\cdot}05°$ C.

DERIVED RESULTS.

Effective force on brake $= L - S = 2 - 0{\cdot}2 = 1{\cdot}8$ lb.
Torque on brake $= 1{\cdot}8 \times \frac{1}{2} \times 0{\cdot}25$ lb. ft.
$= 0{\cdot}225$ lb. ft.
Work done on brake $=$ torque $\times$ radians,
or $=$ force $\times$ circumference $\times$ no. of revs.
$= 1{\cdot}8 \times \pi \times 0{\cdot}25 \times 368$
$= 519{\cdot}98$ **ft. lb.**

Heat given to water and drum
$=$ (weight of water + water equiv.) $\times$ temp. rise
$= W \times (T - t) = 0{\cdot}1799 \times (21{\cdot}05 - 19)$
$= 0{\cdot}1799 \times 2{\cdot}05$
$= 0{\cdot}3688$ **C.H.U.**

Then to find the mechanical equivalent of heat:

$$0{\cdot}3688 \text{ C.H.U.} = 519{\cdot}98 \text{ ft. lb.}$$

$$1 \text{ C.H.U.} = \frac{519 \cdot 98}{0 \cdot 3688} \text{ ft. lb.}$$

$$= 1409 \text{ ft. lb.}$$

Mechanical equivalent of heat $\quad$ **= 1409 ft. lb. per C.H.U.**

NOTE.—*The correct value of this equivalent is* 1400 *ft. lb. per C.H.U., and it will be noticed that the value obtained experimentally is above this value. If all the mechanical energy given to the brake were converted into heat and given to the water and calorimeter, a slightly larger rise in temperature would be evident with a lower value for the equivalent. Actually some heat is lost in the conversion with a resultant increase in the experimental value of the equivalent.*

Summary of energy units.

The **unit of work** or energy is the work necessary in overcoming a resistance of 1 lb. wt. through a distance of 1 ft. measured in the direction in which the resistance is overcome.

Power is the rate of doing work. 1 **horse power** is equivalent to 33,000 ft. lb. per minute or 746 watts or 0·746 kilowatt (p. 289).

The **horse-power hour** is a large unit of energy, and is the amount of work done when one horse power is maintained continuously for 1 hour or $33{,}000 \times 60 = 1{,}980{,}000$ ft. lb. = 1414 C.H.U. = 2545 B.Th.U.

The **Kilowatt-Hour (kWh)** or **Board of Trade Unit** (B.T.U. or B.o.T. unit) is equivalent to 1·3401 horse-power hours and is a power of 1 kilowatt maintained continuously for 1 hour.

$$1 \text{ kWh.} = 1896 \text{ C.H.U.} = 3412 \text{ B.Th.U.}$$

Example 1. *A man while rowing is working at the rate of* 4000 *ft. lb. per minute. What weight of carbon does this expenditure of energy represent when taken over an* 8 *hour day? C.V. of carbon* 14,650 *B.Th.U. per lb. Convert this output of power to horse power and kW.*

Work done in 8 hours $= 4000 \times 60 \times 8$ ft. lb. = **1,920,000 ft. lb.**

Equivalent heat energy $= \dfrac{1{,}920{,}000}{778} = 2467$ B.Th.U.

Least wt. of carbon necessary to produce this energy $= \dfrac{2467}{14{,}650}$

$= \mathbf{0 \cdot 168}$ **lb.**

Horse power developed $= \dfrac{4000}{33{,}000} = \mathbf{0 \cdot 121}$

Output in kilowatts $= 0 \cdot 121 \times 0 \cdot 746 = \mathbf{0 \cdot 09}$.

Example 2. *Heavy tar oil or creosote has a calorific value of* 8,900 *kilogram calories per kilogram and its specific gravity is* 1·084. *Find the heat and mechanical energy stored in* 1 *gallon of oil.* 1 *kilogram* = 2·2 *lb. nearly.* 1 *gallon of water weighs* 10 *lb.*

1 gallon of tar oil weighs $1 \cdot 084 \times 10$ or 10·84 lb.

8,900 kilogram calories per kilogram is equivalent to 8,900 C.H.U. per lb.

$\therefore$ heat energy available $= 10 \cdot 84 \times 8{,}900$ C.H.U. = **96,476 C.H.U.**

Mechanical energy available $= 96{,}476 \times 1{,}400 =$ **135,066,400 ft. lb.**

Example 3. *If the calorific value of petrol is* 20,000 *B.Th.U. per lb. and its specific gravity is* 0·725, *find the energy stored in ft. lb., horse-power hours and kWh. per gallon of petrol.*

1 gallon of petrol weighs 7·25 lb.

7·25 lb. of petrol could produce $7 \cdot 25 \times 20{,}000$ or 145,000 B.Th.U.

$= 145{,}000 \times 778$ or **112,810,000 ft. lb.**

$$= \frac{112{,}810{,}000}{33{,}000 \times 60} = \mathbf{58 \cdot 31 \text{ H.P. hours.}}$$

$= 58 \cdot 31 \times 0 \cdot 746 =$ **43·5 kWh.**

Example 4. *What is the thermal efficiency of a car engine maintaining an output of* 8 *horse power and consuming* 5 *pints of petrol (as in Example* 3) *per hour?*

$$\text{Output} = 8 \times 33000 \text{ ft. lb. per min.} = 264{,}000 \text{ ft. lb. per min.}$$

$$\text{Input} = \frac{5}{8} \times \frac{112{,}810{,}000}{60} \text{ ft. lb. per min.} = 1{,}175{,}104 \text{ ft. lb. per min.}$$

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{264{,}000}{1{,}175{,}104} \times 100 = \mathbf{22 \cdot 47\%}.$$

Characteristics of common fuels.

Solid fuels have the advantage that they do not need special containers. The principal solid fuels are :

Anthracite. This contains 90% carbon and only a small percentage of volatile matter. The fuel is therefore comparatively smokeless and there is little flame. It is very valuable for steam-raising and general power purposes, but requires a strong draught and a thin fire. It has a high calorific value.

Bituminous coal. This coal has a high volatile content. There are many varieties. The carbon percentage varies from 75 to 90. It is very resistant to weathering and burns with a yellow smoky flame. The non-caking varieties are used for steam-raising, while the caking

varieties are used in the manufacture of coke. The well-known Welsh steam coals are really intermediate between anthracite and bituminous coal.

Cannel coal. *A high percentage of oil and gas can be obtained from this type of coal, but it often has a high ash content.*

Lignite is intermediate between bituminous coal and peat. It contains when dry 60 to 75% of carbon, but easily crumbles on drying and does not store well. However, thick seams occur near the surface, which means that it is easily and cheaply worked.

Peat is a spongy humified substance found in boggy land. It has a large water content, and about 5 tons of air-dried peat are equivalent to 3 tons of domestic coal for heating purposes. It has a characteristic odour when burning, which it does readily with a smoky flame. It can be used for boiler firing if briquetted or pulverised.

Coke is produced if coal is heated in the absence of air. Gas and tar vapours are also given off and form useful by-products. Coke is the residue which remains in the furnace. Caking coal gives the best coke. Coke is used in the blast furnace for the reduction of iron ore.

Charcoal is produced if wood is heat-treated in the absence of air.

Briquettes are prepared from dust or " fines " by moulding under pressure either with or without a binding material. The latter may be pitch, coal tar, crude oil, clay, etc. Germany occupies a premier place in the manufacture of briquettes from lignite. Pitch briquettes have a higher calorific value than coal.

All the above fuels can be used in pulverised form.

The advantages of **liquid fuels** are :

(1) The quality is usually more uniform, with the exception of perhaps pulverised fuels.

(2) Not so liable to spontaneous combustion as coal.

(3) For the same calorific value it is much lighter than coal—occupies only about half the volume, and may be stored in double bottoms of ships and leave bunker space for cargo.

(4) No labour is required in handling or trimming the fuel in the furnace, the furnace temperature being more constant.

(5) No labour is required to remove the ash or clinker.

Natural petroleum supplies almost all the liquid fuels used. Crude petroleums are heated in the absence of air, and subjected to fractional distillation; various liquid products are vaporised and driven off at different temperatures. The more volatile substances first driven off are used as motor spirit. Other fractions are paraffin, fuel oil, lubricating oil, and a heavy viscous residue is left in the still after distillation.

Artificial liquid fuels are also being manufactured from coal, tar, etc., on an increasing scale.

Gaseous fuels and their advantages :

(1) No smoke or ash produced.

(2) The high thermal efficiency can be fully utilised.

(3) The fuel can be easily distributed.

(4) Flame is easy to control, varying temperatures can be obtained, and also either oxidising or reducing flames can be produced.

Natural gas usually occurs in conjunction with petroleum and consists chiefly of methane and other light hydrocarbons. An impervious covering of rock usually prevents its escape until freed by drilling.

Coal gas is obtained by the heating of coal in the absence of air and consists mainly of hydrogen, carbon monoxide, and various hydrocarbons. It is stored in large gasometers after being cleared of tarry matter, and is used widely in gas-fired boilers and for commercial purposes.

Other gaseous fuels include :

(1) **Water gas,** obtained by passing steam and air alternately through carbonaceous matter kept at red heat. Its chief constituents are hydrogen, carbon monoxide and various hydrocarbons such as methane.

Carefully proportioned quantities of air and steam passed together through carbonaceous matter at red heat yields a similar gas called **producer** or **suction gas** ; this gas is very suitable as a fuel for gas engines.

(2) **Blast furnace gas,** a by-product of the blast furnace, is composed mainly of carbon monoxide, nitrogen and carbon dioxide.

(3) **Coke oven gas,** a by-product in the production of coke, consists chiefly of hydrogen and hydrocarbons.

Advantages of Pulverised fuel.

(1) More efficient and rapid combustion, and therefore a high temperature of combustion.

(2) Combustion is more complete, there being no carbon loss in ash.

(3) Any class of coal can be used.

(4) Greater control in operation, since fuel can be cut off automatically or supply adjusted to the load.

(5) There is no wastage due to the production of smoke.

(6) Reduced cost in firing boiler.

EXERCISES ON CHAPTER I

Thermometry.

1. Convert the following temperatures to the Fahrenheit scale : (*a*) 15° C., (*b*) 75° C., (*c*) 4° C. What Centigrade temperature corresponds to the following Fahrenheit temperatures : (*d*) 170° F., 400° F. ?

2. Convert – 273° C. to Fahrenheit and – 460° F. to Centigrade.

3. The melting points of ether and sulphuric acid are respectively – 47° F., – 13° F., while the boiling points of alcohol and petroleum are respectively 173° F. and 150° F. Convert these temperatures to Centigrade.

4. The temperatures of melting of mercury, lead, brass, gun-metal, nickel, gold and tungsten are respectively − 39° C., 326° C., 900° C. 1000° C., 1550° C., 1063° C. and 3382° C. Convert these temperatures to Fahrenheit readings.

5. If the upper and lower fixed points on the Réaumur (German) temperature scale are respectively 80 and 0, find what the temperatures 25° C., 50° C. and 120° F. would be on a Réaumur scale.

6. At what temperature do the Centigrade and Fahrenheit scales record the same reading?

7. Describe the construction of a mercury-in-glass thermometer. How are the fixed points determined and how is the thermometer graduated?

Effects of heat.

8. State the possible effects of applying heat to a substance. What is the effect of heating two strips of different metals which have been riveted together?

9. Describe how the engineer makes provision for the expansion of the material he uses. Give instances where the force exerted by a metal as it contracts may be utilised.

10. Define the three coefficients of expansion and state the approximate relation between them.

11. Describe an experiment for determining the coefficient of linear expansion of a metal tube or rod.

12. Three dimensions on an aluminium bronze casting are 8 in., 1 ft. 3 in. and 1 ft. 6 in. What should be the dimensions on the pattern? Allow $\frac{1}{4}$ in. per foot for shrinkage?

13. The diagonal stay of a boiler is 8 ft. long at 60° F. Find its length at 500° F. Coefficient of linear expansion = 0·0000062 per Fahr. degree.

14. An endless wire used on an aerial wire ropeway is 4000 ft. long at 32° F. What is the increase in its length if the temperature rises to 72° F.? Coefficient of linear expansion = 0·000012 per Cen. degree.

15. A crank is bored to a diameter of 5·975 in., and it is to be shrunk on to a shaft 6 in. in diameter, both measurements being made at the same temperature. Find the minimum rise of temperature necessary. Coefficient of linear expansion = 0·000011 per Cen. degree.

16. The density of copper at 0° C. is 554·5 lb. per cu. ft. What will the density be at 100° C.? Coefficient of linear expansion of copper = 0·00001678 per Cen. degree.

17. Glycerine weighs 1260 grams per litre at 0° C. Estimate the weight of a gallon of glycerine at 0° C. and at 100° C. Coefficient of cubical expansion of glycerine = 0·00053 per Cen. degree; 1 lb. = 453·6 grams and 1 gallon = 4·536 litres.

Heat quantities, specific and latent heat.

18. Define the Centigrade heat unit, the British thermal unit, the gram calorie and the therm.

19. Define the term " specific heat ". What information is necessary before the quantity of heat possessed by a body can be measured?

20. If 50 lb. of glycerine at 10° C. is mixed with 40 lb. of pure water at 60° C., what is the resulting temperature of the mixture if no heat is lost. Specific heat of glycerine = 0·58.

21. A roll of aluminium foil weighing 50 grams is placed in the flue gases before they enter the economiser attached to a Lancashire boiler. The foil afterwards raises the temperature of 400 grams of water, originally at 10° C., through 10 Cen. degrees. Estimate the temperature of the flue gases. Specific heat of aluminium over the range of temperature = 0·24.

22. The heat generated by the combustion of 1 gram of fuel oil is absorbed by 2800 grams of water originally at 15° C. If the temperature of the water is raised to 18·9° C. estimate the heat evolved by 1 lb. of the fuel oil when it is burnt.

23. Distinguish between (*a*) sensible heat, (*b*) latent heat of fusion and (*c*) latent heat of vaporisation.

If the specific heat of steam is 0·5, find the amount of heat required to raise 50 lb. of steam through 130° C.

24. 45 lb. of water per minute pass through the cooling jacket of a 100 H.P. Diesel engine and then to an exhaust heater. In the latter the water is raised from 134° F. to 180° F., while the temperature of 23 lb. of exhaust gas per minute drops from 770° F. to 320° F. Calculate the efficiency of the heat transfer in the exhaust heater, taking the mean specific heat of the exhaust gases as 0·25.

25. How much sea water (specific heat 0·94) at 10° C. would be necessary to condense 1 lb. of steam at atmospheric pressure (latent heat of vaporisation 539·9 C.H.U. per lb.) if the final temperature of the sea water and condensed steam is 20° C.?

26. Find the heat necessary to melt 1 lb. of lead originally at 15° C. Melting point of lead, 327° C. Specific heat, 0·0314. Latent heat, 5·4. If in a furnace 0·28 cu. ft. of gas is used per lb. of lead melted, calculate the efficiency of the furnace. Calorific value of gas = 280 C.H.U. per cubic foot as used.

27. What is meant by the terms " water equivalent " and " water value " of a body or of apparatus?

A feed water heater for a boiler weighs 160 lb. and the specific heat of steel is 0·118. Calculate its water value. If the heater contains 200 lb. of water, what is the water value of the whole system?

28. In hardening a sample of steel weighing 10 lb. it is heated to 700° C., and is then plunged into a bath of oil or quenched to reduce its

temperature quickly to 250° C. The weight of the oil is 80 lb. and its specific heat is 0·47, and the specific heat of the steel is 0·12. Assuming the whole of the oil increases uniformly in temperature, find the temperature of the oil at which the sample of steel should be removed.

29. The specific heat of air at constant pressure is 0·238, and 12·35 cu. ft. of air in a room weighs 1 lb. What quantity of heat is required to raise the temperature of the air per Fahr. degree per 1000 cubic feet of air?

Pressure and its measurement.

30. Explain the meaning of the term "standard pressure".

If the weight of 1 cu. in. of mercury weighs 0·49 lb., convert a pressure of 26 in. of mercury to lb. per sq. in.

31. Distinguish between *absolute pressure* and *gauge pressure.*

A pressure gauge records a steam pressure of 185 lb. per sq. in. inside a boiler. What is the absolute pressure of the steam if the barometer reading is 30·5 in. of mercury? Specific gravity of mercury = 13·6.

32. Describe a method of measuring small gauge pressures.

A manometer attached to a gas pipe records a pressure of 5 in. of water while the barometer reading is 29·6 in. What is the absolute pressure of the gas? Specific gravity of mercury = 13·6.

33. Sketch and describe an instrument for measuring pressures less than atmospheric. What is the absolute pressure corresponding to a vacuum of 29 in. of mercury. Barometer reading 30 in. of mercury.

34. Sketch and describe a Bourdon pressure gauge.

35. Describe with sketches a method of testing and calibrating pressure gauges.

36. Describe one instrument for measuring pressures below atmospheric, and also one instrument suitable for measuring high pressures.

37. Distinguish between gauge and absolute pressure. Express a pressure of 250 lb. per square inch gauge as absolute pressure if the atmospheric pressure is 14·7 per square inch.

Combustion and calorific value.

38. What do you understand by the term *fuel,* and what are the chief constituents of a fuel?

39. Distinguish between *oxidation* and *combustion,* and explain the meaning of the terms *point of ignition, flash point* and *spontaneous combustion.*

40. Describe how combustion is controlled in either (*a*) a boiler furnace, or (*b*) an internal combustion engine. Why must excess air usually be supplied?

41. State the laws of chemical combination. The chemical formula for methane is CH_4. Calculate the minimum quantity of air necessary to consume 1 lb. of this gas.

42. Calculate the minimum amount of air required to burn 1 lb. of Welsh steam coal containing 84% carbon, 4·8% hydrogen and 1·4% of sulphur. Neglect the oxygen content of the fuel.

43. Calculate from first principles the amount of air necessary to burn completely 1 lb. of carbon to carbon monoxide (CO) and also to carbon dioxide (CO_2).

44. State the approximate composition of air (*a*) by weight, (*b*) by volume. The chemical composition of a sample of peat is 58% C, 6·3% H, 30·8% O, 0·9% N and 4% ash, and a trace of sulphur. Calculate the minimum quantity of air per lb. of peat required for complete combustion.

45. A sample of fuel oil as used in a Diesel engine consists of 86% C and 14% H. Find the air supply necessary for complete combustion if the excess air is 30% of the minimum amount. Also find the weight of the exhaust gases per lb. of fuel oil burnt.

46. A sample of fuel oil contains 84% C, 14% H, 1·5% O and 0·5% N. Calculate the minimum air required for complete combustion. If 50% excess air is supplied, find the weights of flue gases generated per lb. of fuel.

47. The air supply to a petrol engine is 15 lb. of air per lb. of petrol and the air temperature is 60° F. Calculate the heat carried away by the exhaust gases per lb. of fuel if the mean specific heat of the gases is 0·24, and the temperature of the exhaust is 790° F.

48. Distinguish between the gross and net calorific value of a fuel. A sample of boiler coal contains 79%C, 5% H, 7% O, 1½% N, 1½% S, and ash 6%. Find the minimum air and the approximate net and gross calorific values per lb.

49. The chemical composition of metallurgical coke has the following analysis: 88% C, ½% H, 1% N, 0·9% S, 0·9% O and 8·7% ash. Find the minimum air for complete combustion and the gross calorific value per lb. of coke.

50. A sample of fuel oil for a boiler has the following chemical analysis: 87% C, 7% H, 2% O, 4% N. Estimate the gross and net calorific values per lb.

51. Describe a fuel calorimeter, and show how it can be used to calculate the calorific value of a sample of coal.

52. Calculate the calorific value of a sample of Yorkshire caking coal from the data given:

Weight of coal	=0·006 lb.
Weight of water in calorimeter	=5 lb.
Temperature ,, ,, ,,	=56° F.
Final ,, ,, ,,	=69·6° F.
Water equivalent of apparatus	= 0·9 lb.

53. Calculate the approximate calorific value of a sample of refined Russian petroleum oil.

Weight of oil	$=0\ 0055$ lb.
Weight of water in calorimeter	$=6$ lb.
Temperature of water in calorimeter	$=16°$ C.
Final ,, ,, ,, ,, ,,	$=25°$ C.
Water equivalent of apparatus	$=0\ 9$ lb.

54 Calculate the calorific value of a sample of coal in B.Th.U. per lb. and in C H U. per lb. from the following experimental results.

Wt. of coal	$=1\ 03$ gram.
Wt of water	$=2315$ grams.
Initial temperature of water in calorimeter	$=13\ 75°$ C.
Final temperature of water in calorimeter	$=16\ 70°$ C.
Water equivalent of apparatus	$=425$ grams.

55 What is *Avogadro's law*? Find the density of methane (CH_4) at normal temperature and pressure if hydrogen weighs 0 00559 lb. per cu ft at normal temperature and pressure (N T.P.).

56 Calculate the volume of air required to burn 1 cu ft of methane (CH_4) at N.T P. What is the percentage reduction of volume with the least amount of air if the products of combustion are assumed to be reduced to atmospheric temperature and pressure?

57 Calculate the least volume of air required to burn completely 1 cu ft of hydrogen, and the percentage reduction in volume after combustion

58 Give a brief description of a gas calorimeter.

59 Determine the calorific value of coal gas in B.Th.U. per cu. ft. from the following experimental results

Volume of coal gas burnt, measured at 60° F. and 30 in. of mercury = 0 325 cu. ft.

Wt of water = 1560 grams. Initial temperature of water = 14 6° C.

Final temperature of water = 40 9° C

NOTE.—1 gram calorie = 0 003968 B.Th U.

Conversion of energy and miscellaneous examination questions.

60 How many B Th U. and C H U. of heat energy are available when 370,000 foot pounds of mechanical energy are converted to heat energy ?

61. Find the rise of temperature in Fahrenheit degrees produced in 10 gallons of water by the heat equivalent of the mechanical energy expended in raising 6 tons to a height of 20 ft.

62. A fuel has a calorific value of 15,000 B.Th U. per lb. Find the work equivalent if the efficiency of combustion is 40%.

63. A locomotive consumes 4 tons of coal of average calorific value 11,000 B.Th.U. per lb. on a journey of 4 hours' duration. The engine has a H P. of 1050 ; find the overall efficiency.

64. What weight of coal of calorific value 11,500 B.Th.U. per lb. is consumed in one hour by a boiler serving a 140 H.P. engine if the overall efficiency of boiler and engine is $12\frac{1}{2}\%$?

65. A dyeing works requires to heat 4000 gallons of water from 55° F. to 210° F. every hour. What would you expect the coal consumption to be if the efficiency of the boiler is 18% and the C.V. of the fuel 12,000 B.Th.U. per lb. ?

66. In a pulverised fuel furnace 35,000 B.Th.U. are liberated per minute per cubic foot of furnace volume. Calculate the least weight of coal required per cubic foot of furnace volume per minute if the calorific value is 12,000 B.Th.U. per lb.

67. A Beardmore-Blake boiler working at 165 lb. per sq. in. burned 328·6 lb. of oil fuel in 1 hour while evaporating 4197 lb. of water. If the calorific value of the oil is 19,000 B.Th.U. per lb., and if each pound of water receives 1170 B.Th.U., calculate the efficiency of the boiler.

68. Using the table of calorific values given below, calculate the theoretical horse power developed corresponding to the burning of 1 lb. of each fuel per minute.

	B.Th.U. per lb.		B.Th.U. per lb.
(*a*) Peat (air-dried) -	10,000	(*e*) Kerosene - -	19,000
(*b*) Newcastle steam coal	14,700	(*f*) Petrol - -	18,450
(*c*) Scotch cannel - -	13,500	(*g*) Trinidad crude oil - - -	18,400
(*d*) Welsh anthracite -	15,200	(*h*) Russian fuel oil -	19,400

69. What is meant by the term "*mechanical equivalent of heat*"? Describe an experiment for its determination.

70. A gas engine is consuming 2·14 cu. ft. of gas per min., and the calorific value of the gas is 491 B.Th.U. per cu. ft. If the output of the engine is 4·7 H.P. find the thermal efficiency of the engine.

71. If a Diesel engine uses 0·4 lb. of oil of calorific value 19,000 B.Th.U. per lb. per B.H.P. per hour, what is its thermal efficiency.

72. 40 lb. of water in an absorption dynamometer is raised in temperature 36° F. What quantity of kinetic energy in ft. lb. has been absorbed.

73. The combustion of 1 lb. of petrol generates 18,000 B.Th.U. For how long would this petrol propel a 10 H.P. car if only 20% of the energy available is usefully employed?

74. At 2350 r.p.m. the petrol consumption per hour at full throttle of an aero-engine is 9·75 gallons. If the B.H.P. is 130 and the calorific value of the petrol 18,750 B.Th.U. per lb., estimate the thermal efficiency of the engine. Specific gravity of petrol = 0·78.

75. If the latent heat of the petrol used (Question 74) is 132 B.Th.U./lb., find the energy in ft. lb. necessary to evaporate 10 gallons of petrol of specific gravity 0·78.

76. A high pressure gas burner giving out 1000 candle power consumes gas of calorific value 500 B.Th.U. per cu. ft. at the rate of 40 cu. ft. per hour. If 7% of the heat energy available is converted into light, what is the equivalent of 1000 candle power in B.Th.U. per minute.

77. A 1500 watt lamp gives out a candle power of 2340 when new. Convert this output of energy to B.Th.U. per minute per 1000 candle power.

78. In the determination of Joule's equivalent by Callendar's apparatus the friction produced by a net brake load of 4123 gm. acting at a radius of 3 in. raised the temperature of 345 gm. of water inside the brass drum through 1·18° C. after 100 rev. of the drum. Calculate the value of Joule's equivalent. Water equivalent of apparatus = 42·2 gm.

79. A locomotive burns 560 lb. of fuel of calorific value 11,500 B.Th.U. on a run of 30 miles. The average draw bar pull was 2500 lb. What is the thermal efficiency of the locomotive ?

80. Define the terms "calorific value", "ignition temperature", "minimum air", "excess air", "products of combustion", "mechanical equivalent of heat", and "unit of heat".

81. Assuming the specific heat of iron remains at 0·115, find how much coal must be consumed to raise the temperature of the metal of a furnace through 1500 Fahr. degrees. Weight of iron, 3 tons. C.V. of coal, 13,000 B.Th.U. per lb. Efficiency of operation, 84%.

82. What is the specific heat of a substance ?

If 100 gm. of water at 100° C. are poured into 120 gm. of turpentine at 9° C. and the resulting temperature found to be 70° C., what is the specific heat of the turpentine ? What reason have you for supposing that the result you give may not be correct ? (U.L.C.I.)

83. What is meant by specific heat, latent heat, sensible heat ?

During an experiment to find the specific heat of copper the following observations were made :

Wt. of copper calorimeter empty	= 60 gm.
Wt. of copper calorimeter plus water	= 290 gm.
Initial temperature of water and calorimeter	= 16° C.

140 gm. of copper at 100° C. were placed in this calorimeter, and the final temperature of the water was found to be 20·5° C. From this data calculate the specific heat of copper. (U.L.C.I.)

84. What do you understand by coefficient of linear expansion ?

A copper pipe in a heating system is 30 ft. long at the normal temperature of 15° C. ; find its length when water at a temperature of 85° C. flows through it. Coefficient of expansion of copper per °C. = 0·000017. (U.L.C.I.)

CHAPTER II

THE HEAT ENGINE—WORKING SUBSTANCES AND THEIR PROPERTIES—THE GAS LAWS—STEAM TABLES AND STEAM QUANTITIES—MEASUREMENT OF HIGH TEMPERATURES

The heat engine. The change of heat into mechanical energy is a difficult matter to perform efficiently, and a heat engine is used to bring about the transfer. The definite relation, discovered by Joule, between the two kinds of energy has made it possible for the engineer to find whether his boiler and engine are making the best use of the heat energy supplied by the fuel. The engineer can draw up a balance sheet to show the proportion of heat energy actually converted into useful mechanical work, and what is wasted, and how it is wasted.

Even in the most up-to-date and efficient plant there is still a great loss of energy. To understand this it must be remembered that a heat engine uses a gas or vapour to effect the transfer of energy. This gas or vapour is called the **working substance** and to do work it must expand and remain expanded, and thus hold a considerable proportion of its heat energy. When this expansion has reached its useful limit the expanded substances are often discarded, as in the locomotive and motor car. In stationary engines the exhaust heat is often utilised. The exhaust steam from reciprocating engines can be usefully employed to drive low-pressure turbines, or for heating or industrial purposes. In any event, it appears that the conversion of energy can be most efficiently done in stages.

It must be emphasised that neither the working substance nor any of its energy is destroyed while passing through the heat engine. The laws of conservation of matter and energy can be quoted in support of this statement. Matter and energy can be changed in character but never destroyed.

Example. *A column of air of volume* 6·195 *cu. ft. and at* 0° *C. is enclosed in a cylinder of* 1 *sq. ft. cross-sectional area and supports a piston weighing* 2117 *lb. The air is heated at constant pressure up to* 200° *C., causing it to expand and do external work by raising the piston. The air weighs* 1 *lb., and its specific heat at constant pressure is* 0·2375 (*see table*). *Coefficient of expansion* $= \frac{1}{273}$ *per cu. ft. per degree C. Find the thermal efficiency of the operation.*

The piston will only remain raised if the air retains the heat energy necessary for it to remain expanded. Thus only a proportion of the energy supplied has been converted to mechanical work.

Expansion of air

= volume × coefficient of expansion × rise of temperature

$= 6{\cdot}195 \times \frac{1}{273} \times 200 = 4{\cdot}535$ cu. ft.

Height piston is raised $= 4{\cdot}535/1 = 4{\cdot}535$ ft.

Work done in raising piston $= 2117 \times 4{\cdot}535 = 9600$ ft. lb.

Equivalent heat energy $= 9600/778 = 12{\cdot}33$ B.Th.U.

Heat to expand air and do work

= mass × specific heat × rise of temperature

$= 1 \times 0{\cdot}2375 \times 200 = 47{\cdot}5$ B.Th.U.

Heat retained to keep air expanded (ineffective work)

= heat to expand − external work done

$= 47{\cdot}5 - 12{\cdot}33 = 35{\cdot}17$ B.Th.U.

Percentage of heat usefully employed, or

$$\text{thermal efficiency of the operation} = \frac{12{\cdot}33}{47{\cdot}5} \times 100 = 25{\cdot}9\%.$$

In this expansion, to simplify the problem, heat is supposed to be supplied at constant pressure, the piston is assumed to be air-tight and cylinder expansion is neglected. If a cast iron column had been used instead of an air column, only about $\frac{1}{2}$% of the heat supplied would have been converted into work. This is because cast iron expands very little when heated. Therefore as working substances for heat engines, gases and vapours are much better than solids and liquids. The ideal working substance must possess great expansibility and a low specific heat: that is, it must be capable of great expansion, which can be produced by very little heat. In the steam engine, heat is taken in in a separate vessel called the boiler during the process of vaporisation. The steam is allowed to expand in the engine cylinders, and the work done is mainly supplied by the internal

heat energy possessed by the steam. In the internal combustion engine the working substances are the products of rapid combustion or explosion of a mixture of fuel and air. Here again the working substances draw on their own stock of internal heat energy to perform external work, and the temperature and pressure fall in the process.

The following comparison may be of interest:

Cost of food (20 lb. of oats and 20 lb. of hay per horse) for 20 large horses working for 8 hours = 43 shillings approx.

Cost of petrol (14 gallons) and oil for a 20 brake horse power engine working for 8 hours = 18 shillings approx.

A good modern Diesel oil engine will consume about 0·35 lb. of fuel per hour per brake horse power, representing a conversion into useful work of 38·3% of the heat energy in the fuel. The corresponding figures for a gas and a petrol engine are respectively 25% and 23%. An oil-fired boiler and steam engine would burn 0·6 lb. of fuel per hour per B.H.P., representing a conversion of 20%. The water tube boiler of modern design can transfer 88% of the heat energy in the fuel into the steam it produces, while the steam turbine will convert 31% of the energy in the steam at the stop valve into electrical energy when driving a generator. The ratio

$$\frac{\text{heat converted into work}}{\text{heat supplied}}$$

is called the **thermal efficiency of an engine.**

Properties of working substances. Gas is the general term used to denote one of the three states, solid, liquid and gaseous, in which matter can exist. Liquids and gases are sometimes classified as fluids. A gas under pressure has elastic properties and will always fill a container whatever its size, and many gases need great pressures and low temperatures to liquefy them. When a gas approaches its liquid state it becomes a vapour. A perfect gas is one which obeys **Boyle's Law,** which states that *the absolute pressure P and volume V of a given mass of gas are inversely proportional, that is,*

$$P \times V = P \div \frac{1}{V} = \textit{constant},$$

provided the temperature remains constant.

A gas expanding according to Boyle's Law is said to expand **isothermally** (that is, without change of temperature), and the pressure v. volume graph is a curve known as the rectangular hyperbola. Sometimes the expansion is called hyperbolic, although hyperbolic expansion is not necessarily isothermal expansion.

EXPT. 16. **Relation between pressure and volume of a gas.**

OBJECTS. *To verify Boyle's Law for a gas, that is, to show that the volume of a gas is inversely proportional to its pressure when the temperature is constant.*

APPARATUS. Boyle's Law apparatus (Fig. 20), which consists of two glass tubes attached to slides whch can be moved upward and downward on a vertical fixed scale. The two tubes are connected by a length of stout rubber tubing, and one of the tubes B has an open end, while the other A is closed with a glass cock. The rubber tube is filled with mercury and a certain weight of air is trapped in the closed tube A.

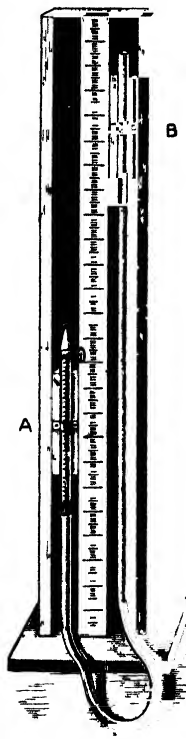


FIG. 20. Boyle's law apparatus.

METHOD OF PROCEDURE. The slides A and B are adjusted with the cock on A open until about half the volume of A contains air and the mercury levels in A and B are the same. Thus the air in A is subjected to atmospheric pressure. The cock on A is then closed. Next B is raised so that the air in A becomes subjected to a pressure equal to atmospheric plus a mercury height equal to the difference in the mercury levels of A and B. For example, if the barometer reading is 30 in. of mercury, and the difference of mercury levels on A and B is 12 in., the air in A is subjected to a pressure equivalent to $30 + 12$ or 42 in. of mercury. From the scale the length of the air column in A can be read, and this reading is proportional to the volume of the air. A series of observations for varying pressures and volumes are taken and a graph drawn of pressure against volume. If another graph is drawn of pressure against $\frac{1}{\text{volume}}$, this second graph will be a straight line passing through the origin, thus showing that pressure is *inversely* proportional to volume. The student should calculate the product of pressure and

volume for each observation. These products should produce a constant within the limits of experimental accuracy. *Thus Boyle's Law may be expressed as Pressure × Volume is a constant when the temperature of a gas is kept unchanged.*

OBSERVATIONS.

Barometer height	Difference of mercury level	Press. on air (P)	Volume of air (V)	$P \times V$.	$\frac{1}{V}$
30 in.	5 in.	35 in.	3·5 in.	122·5	0·286
30 in.	10 in.	40 in.	3·0 in.	120	0·333
30 in.	15 in.	45 in.	2·65 in.	119·3	0·378
30 in.	20 in.	50 in.	2·45 in.	122·5	0·408
30 in.	0 in.	30 in.	4 in.	120	0·25

GRAPHS.

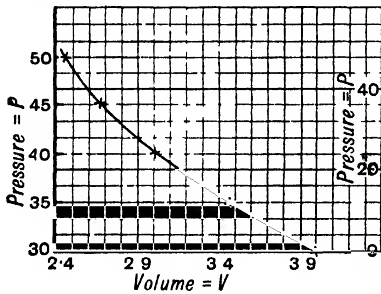


FIG. 21. *Pv . V*

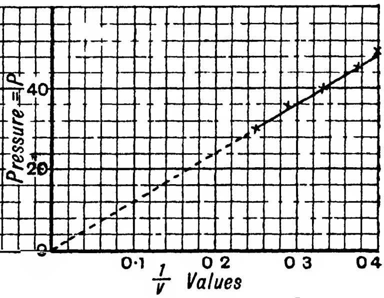
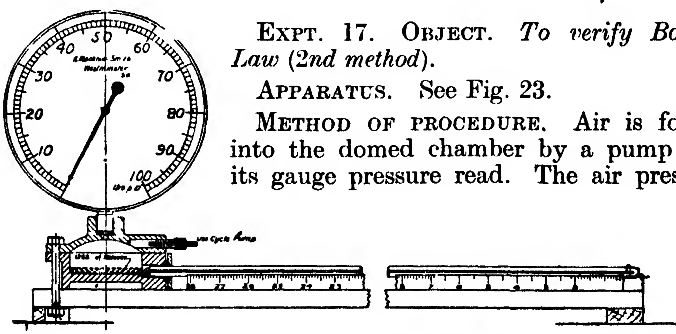


FIG. 22. *Pv .* $\frac{1}{V}$



EXPT. 17. OBJECT. *To verify Boyle's Law (2nd method).*

APPARATUS. See Fig. 23.

METHOD OF PROCEDURE. Air is forced into the domed chamber by a pump and its gauge pressure read. The air pressure

FIG. 23. Boyle's Law apparatus.
(A. Macklow Smith, Ltd.)

forces mercury into the capillary tube on the right and compresses the air imprisoned in it. The length of this quantity of air is a measure to some scale of its volume, and these lengths are tabulated against the absolute pressure of the gas.

OBSERVATIONS.

Barometric pressure $= 29{\cdot}5$ in. of mercury
$= 14{\cdot}45$ lb. per sq. in.

Temperature constant at $14{\cdot}5°$ C.

Absolute pressure $=$ gauge pressure $+$ barometric pressure.

Volume V or length of air column	Gauge pressure	Absolute pressure, P lb./in.^{2}	$P \times V$
25·63	0	14·45	370·3
15·18	10	24·45	371·1
10·73	20	34·45	369·7
8·28	30	44·45	368·1
7·52	35	49·45	371·9
6·85	40	54·45	373

The values of the products of P and V are, within practical limits, constant. Thus Boyle's Law is verified; that is, the pressure of a gas is inversely proportional to its volume when the temperature is constant.

Charles' Law. Experiments with rather elaborate apparatus show that, when the pressure of a perfect gas is kept constant, and the temperature of the gas is raised, then its volume changes in such a way that the volumes and corresponding temperatures lie on a straight line graph (Fig. 24). Approximate results could be obtained with the apparatus just described, if the capillary tube could be heated by a steam jacket. When the graph is produced backwards to cut the temperature axis, it is found to cut this axis at $-460°$ F. This is called absolute zero, and temperatures

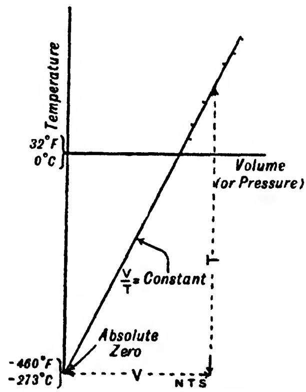


FIG. 24. V varies as T.

read above this are called **absolute temperatures.** Thus 68° F. $=68+460$ or 528° F. absolute. Absolute zero on the Centigrade scale is $-273°$ C., and the absolute temperature is obtained by adding 273° to the normal Centigrade reading. For example,

$$64° \text{ C.} = 64 + 273 = 337° \text{ C. absolute.}$$

This result on the Centigrade Scale was first discovered by the French physicist Charles in 1787. He also found that if the volume was kept constant then the graph of pressures and temperatures cut the temperature axis also at $-460°$ F., or more exactly $-459{\cdot}4°$ F. These laws are often stated thus :

(*a*) *if the volume V of a gas is kept constant, the absolute pressure P is directly proportional to its absolute temperature T, or $P/T = const.$ (if V is const.)* ;

(*b*) *if the pressure of a gas is kept constant, the volume V is directly proportional to its absolute temperature T, or $V/T = const.$ (if P is const.).*

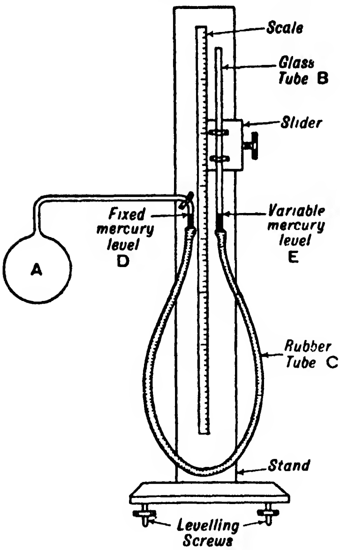


FIG. 25. Charles' law apparatus.

EXPT. 18.

OBJECT. *To verify the first of these Charles' Laws for a gas ; that is, the pressure of a gas which is maintained at constant volume increases by a fraction 1/273 of its pressure at 0° C. for every 1° C. rise in temperature.*

Algebraically this law may be expressed as follows :

$\mathbf{P_t = P_0(1 + \frac{1}{273}t)}$ where P_t is the pressure at $t°$ C., P_0 the pressure at 0° C., and t the rise in temperature in degrees C.

APPARATUS. A wooden stand fitted with levelling screws, and carrying a vertical scale. Attached to the back board (Fig. 25) is a glass bulb A with a bent glass tube connected to a straight glass tube B by an indiarubber pipe C. The tube B is fitted to a slider free to move vertically up and down the back board. The rubber tube is filled with mercury, and A contains

a quantity of air which is trapped by the mercury in the rubber tube and can be heated by immersing the bulb A in a beaker of water.

METHOD OF PROCEDURE. Immerse the bulb A in a beaker of melting ice, and allow it to remain for some time until the air in A is at the temperature of melting ice, that is, 0° C. Adjust the slider so that the mercury levels at D and E are the same. Note the level D. Next immerse the bulb in water and heat the water to a steady 20° C. and maintain this temperature for some time. The level D will fall and level E will rise to meet the expansion of air in A. Raise the tube B until the level of D is restored to its original value, and read off the differences in level of E and D. Then the air in A will be at a pressure equal to barometer reading plus the level difference of D and E. Repeat the experiment for temperatures of 40°, 60°, 80° and 100° C., and tabulate the results. Then in these observations the volume of air in A is kept constant, the temperature has been increased and the pressure has increased. The increase of pressure is the difference of the mercury levels at E and D, so that if α is the coefficient of increase of pressure with temperature when the volume is kept constant,

$$P_t = P_0(1 + \alpha t),$$

in which $$P_1 = P_0(1 + \alpha t_1)$$

and $$P_2 = P_0(1 + \alpha t_2);$$

thus, by division, $$\frac{P_2}{P_1} = \frac{1 + \alpha t_2}{1 + \alpha t_1} \quad \text{.................................}(a)$$

Cross-multiplying in (a), $P_2 + P_2\alpha t_1 = P_1 + P_1\alpha t_2$.

Rearranging, $\alpha(P_2 t_1 - P_1 t_2) = P_1 - P_2$;

$$\therefore \alpha = \frac{P_1 - P_2}{P_2 t_1 - P_1 t_2}.$$

and from this expression a value of α may be calculated. P_2 and P_1 are values of P_t when t has the values t_2 and t_1 respectively.

NOTE 1. There is a possible source of error in this experiment, since the volume of air in A is *apparently* constant. The container expands, but the extent of its expansion is negligible when compared with that of the air in A.

NOTE 2. The value of $\alpha = \frac{1}{273}$ which will be determined from this experiment is the coefficient of increase of pressure with temperature, but since under the consideration of Boyle's Law the increase of pressure is related to the decrease of volume, the value of α is also the coefficient of increase of volume with temperature.

Combination of Boyle's and Charles' Laws.

If $1/273$ be substituted for α in equation (a) of experiment 55, the result will be

$$\frac{P_2}{P_1}=\frac{1+t_2/273}{1+t_1/273}.$$

Multiply the numerator and denominator of the last fraction by 273, and remembering that $273°+t°$ C. is the absolute temperature T, then

$$\frac{P_2}{P_1}=\frac{273°+t_2}{273°+t_1}=\frac{T_2}{T_1}, \text{ or } \frac{P_2}{T_2}=\frac{P_1}{T_1}, \quad \ldots\ldots\ldots\ldots\ldots\ldots(b)$$

when the volume is maintained constant.

In a similar way by keeping the pressure constant the same apparatus can be used to show that $1/273$ is the coefficient of increase of volume per Cen. degree if the initial volume is that at 0° C., and thus

$$\frac{V_2}{T_2}=\frac{V_1}{T_1}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(c)$$

This constitutes the second law of Charles and is exemplified in Fig. 24, where it will be seen that if absolute zero be taken as the origin for the graph, then V is directly proportional to T. However, in the region of absolute zero, even for permanent gases, Charles' law does not hold owing to changes in the state of the gas.

The expressions (b) and (c) are both satisfied by

$$\frac{P_2V_2}{T_2}=\frac{P_1V_1}{T_1}, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(d)$$

since with constant volume $V_2=V_1$, and (d) becomes $P_2/T_2=P_1/T_1$, and with constant pressure $P_2=P_1$, and (d) becomes $V_2/T_2=V_1/T_1$. In (d) the suffixes 1 and 2 indicate a change of conditions of the same mass of gas from the state indicated by the values P_1, V_1, T_1 to the state indicated by the values P_2, V_2, T_2. Thus the quantity

$$\frac{\text{absolute pressure} \times \text{volume}}{\text{absolute temperature}}$$

remains constant, providing the mass of gas is unchanged and Boyle's and Charles' Laws are complied with.

Expression (d) can thus be written $\frac{PV}{T}=K$, where K is a constant depending upon the mass and properties of the gas. It may be written $PV=KT$. A study of this expression will show that a

reduction of P brings about an increase of V, while a reduction of T decreases V, but to a lesser extent because T is already a comparatively large number. The expression (*d*) is extremely useful in making calculations of changes in the conditions of a given mass of gas.

Characteristic equation of a perfect gas. This equation, in symbols, is written $PV = RT$, since it satisfies both Boyle's and Charles' Laws. R is called the **gas constant** when 1 lb. of gas is considered, and in this case V is called the **specific volume** (since it is the volume of 1 lb. of gas), and P is the **absolute pressure** in lb. per sq. ft. $R = 53{\cdot}2$ ft. lb. per lb. per degree F. for air. The characteristic or gas equation is of great importance to the engineer.

Many of the gases which serve as working substances for heat engines behave almost as perfect gases.

When V refers to the volume of w lb. of gas instead of 1 lb., R, the characteristic gas constant, may still be included if the equation is written

$$PV = wRT \quad \text{or} \quad \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \frac{P_3V_3}{T_3} = wRT$$

for three different states 1, 2, and 3 of the gas.

The units in which R is expressed will depend upon those used for P, V, T and w. It is customary to express P in lb. per sq. ft., V in cu. ft., w in lb., and T either in absolute Fahr. or Cen. degrees. Thus the units of R will be, since $R = PV/wT$,

$$\frac{\text{lb.} \times (\text{ft.})^3}{(\text{ft.})^2 \times \text{lb.} \times \text{Cen. or Fahr. degrees abs.}}$$

$$= \text{ft. lb. per lb. per Cen. or Fahr. degree.}$$

R can also be expressed in heat units by dividing by J, the mechanical equivalent of heat, 778 for 1 B.Th.U., 1400 for 1 C.H.U.

It is also worthy of note that the above expression in the form $w = \dfrac{PV}{RT}$ can be used to determine the weight of a quantity of gas when the quantities P, V, R and T are known.

Specific heats of a gas. When any gas is heated at constant pressure its specific heat, written c_p, is found to be greater than its specific heat when heated at constant volume and denoted c_v. The values

of c_p and c_v depend upon the nature of the gas, and their values also alter with the temperature. When a gas is heated at constant volume, no external work is done, so that it is reasonable to suppose that c_v should be less than c_p. Also, when R is in heat units it is found that $R = c_p - c_v$.

Thus, for air, $0{\cdot}0684 = 0{\cdot}2375 - 0{\cdot}1691$ where $c_p = 0{\cdot}2375$ and $c_v = 0{\cdot}1691$.

Hence $R = 0{\cdot}0684 \times 778 = 53{\cdot}2$ ft. lb. per lb. per Fahr. degree.
or $ = 0{\cdot}0684 \times 1400 = 95{\cdot}8$ ft. lb. per lb. per Cen. degree.

The property of gases whereby they can pass through different substances, including gases, is called **diffusion.** When two or more gases are introduced into a closed vessel each will expand in turn to fill the vessel, diffusing through the gas already occupying the space, and the total pressure will be the sum of that due to each gas, the volume of each being the volume of the vessel.

The principal quantitative properties of a gas are its temperature and pressure, the volume of 1 lb. or specific volume, the characteristic constant, specific heat at constant pressure and constant volume and the heat content above some datum temperature.

Example 1. *4 cu. ft. of air at 14·7 lb. per sq. in. abs. and 40° F. are compressed isothermally to 58·8 lb. per sq. in. Calculate the new volume. If the gas is now heated to 440° F. while this new pressure remains constant, find the final volume. Show that the final result can be calculated directly by using the characteristic equation.*

By Boyle's law,

$$P_1V_1 = P_2V_2 \text{ or } V_2 = P_1V_1/P_2 = 14{\cdot}7 \times 144 \times 4/58{\cdot}8 \times 144 = 1 \text{ cu. ft.}$$

By Charles' law,

$$V_3/V_2 = T_3/T_2 \text{ or } V_3 = T_3V_2/T_2 = (460 + 440) \times 1/500 = 1{\cdot}8 \text{ cu. ft.}$$

Using the Characteristic Equation,

$$\left.\begin{array}{l} P_1 = 14{\cdot}7 \times 144 \text{ lb./ft.}^2 \\ P_2 = 58{\cdot}8 \times 144 \text{ lb./ft.}^2 \\ V_1 = 4 \text{ cu. ft.} \\ V_2 \text{ is to be found.} \\ T_1 = 460° + 40° = 500° \text{ F. abs.} \\ T_2 = 440° + 460° = 900° \text{ F. abs.} \end{array}\right\} \frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = wR.$$

$$\therefore\ V_2 = \frac{P_1T_2V_1}{P_2T_1} = \frac{14{\cdot}7}{58{\cdot}8} \times \frac{900}{500} \times 4 = 1{\cdot}8 \text{ cu. ft.}$$

Example 2. *Find the weight of ammonia in a gas cylinder if the volume is 3 cu. ft., the absolute pressure is 20 atmospheres and the temperature 0° F. Take R as 101·92 ft. lb. per lb. per Fahr. degree.*

$P = 20$ atmospheres $= 20 \times 14{\cdot}7 \times 144$ lb./ft.² $\quad T = 459{\cdot}4°$ F. abs.

$V = 3$ cu. ft. $\qquad R = 101{\cdot}92$ ft. lb. per lb. per Fahr. degree.

Since $PV = wRT$, then $w = PV/RT = \dfrac{20 \times 14{\cdot}7 \times 144 \times 3}{101{\cdot}92 \times 459{\cdot}4} = 2{\cdot}714$ **lb.**

Example 3. *If $c_p = 0{\cdot}224$ and $c_v = 0{\cdot}16$ are the specific heats at constant pressure and volume respectively for oxygen, calculate the value of R for oxygen in C.H.U. per lb. per Cen. degree and the density of oxygen at N.T.P.*

$$R = c_p - c_v = 0{\cdot}224 - 0{\cdot}16 = 0{\cdot}064 \text{ C.H.U. per lb. per Cen. degree.}$$

Also $\quad R = 0{\cdot}064 \times 1400 = 89{\cdot}6$ ft. lb. per lb. per Cen. degree.

At N.T.P., $\quad P = 14{\cdot}7 \times 144$ lb./ft.² and $T = 273°$ C. abs.

Also $\qquad V = 1$ cu. ft., since the weight of 1 cu. ft. is required.

$$\therefore\ w = \frac{PV}{RT} = \frac{14{\cdot}7 \times 144 \times 1}{89{\cdot}6 \times 273} = 0{\cdot}08654 \text{ lb. per cu. ft.}$$

Example 4. *An engine consumes 2·14 cu. ft. of coal gas per minute. The temperature and pressure of the gas as used are 65° F. and 31 in. of mercury. What is the gas consumption at 0° C and 30 in. of mercury, and what is the value of the heat received by the engine per minute? Calorific value of gas at N.T.P. = 496 B.Th.U. per cu. ft.*

Initial conditions :	Final conditions, N.T.P. :	
$P_1 = 31$ in. of mercury.	$P_2 = 30$ in. of mercury.	$\dfrac{P_1V_1}{T_1} = \dfrac{P_2V_2}{T_2} = wR.$
$V_1 = 2{\cdot}14$ cu. ft.	V_2 is required.	
$T_1 = 65 + 460 = 525°$ F. abs.	$T_2 = 492°$ F. abs.	

$$V_2 = \frac{P_1}{P_2} \times \frac{T_2}{T_1} \times V_1 = \frac{31}{30} \times \frac{492}{525} \times 2{\cdot}14 = 2{\cdot}072 \text{ cu. ft.}$$

Heat to engine per min. $= 2{\cdot}072 \times 496 =$ **1028 B.Th.U.**

Example 5. *The weight of air dealt with by the forced draught fan of a boiler was 36,000 lb. per hour. Find the volume of this quantity of air at 60° F. and at a pressure of 14·7 lb. per sq. in.? R = 53·2 ft. lb. per lb. per Fahr. degree.*

$w = 36{,}000$ lb. $\quad P = 14{\cdot}7 \times 144$ lb. per sq. ft. $\quad V$ is required.

$T = 460 + 60 = 520°$ F. abs. $\quad R = 53{\cdot}2$ ft. lb. per lb. per Fahr. degree.

$$\therefore \text{ from } PV = wRT, \quad V = \frac{wRT}{P} = \frac{36{,}000 \times 53{\cdot}2 \times 520}{14{\cdot}7 \times 144}$$

$$= 470{,}400 \text{ cu. ft. per hour.}$$

Example 6. *Air, which has been pumped into a diving bell at the bottom of a harbour, occupies 1500 cu. ft., and its pressure and temperature are 35 lb. per sq. in. and 64° F. respectively. What is the volume of this air at atmospheric pressure (14·7 lb. per sq. in.) and temperature 50° F.?*

Now $PV = wRT$ where w is the mass of gas, or $\dfrac{PV}{T} = wR$. Therefore $\dfrac{P_1V_1}{T_1}$ for the initial conditions = const. $= wR = \dfrac{P_2V_2}{T_2}$ for the final conditions.

$$\left.\begin{array}{ll} P_1 = 35 \times 144 \text{ lb. per sq. ft.,} & P_2 = 14{\cdot}7 \times 144 \text{ lb. per sq. ft.} \\ T_1 = 460° + 64° = 524° \text{ F. abs.,} & T_2 = 460° + 50° = 510° \text{ F. abs.} \\ V_1 = 1500 \text{ cu. ft.,} & V_2 \text{ is to be found.} \end{array}\right\} V_2 = \frac{P_1V_1T_2}{P_2T_1}.$$

Then $$V_2 = \frac{35 \times 144 \times 1500 \times 510}{14{\cdot}7 \times 144 \times 524} \text{ or } \mathbf{3477 \text{ cu. ft.}}$$

Notice that 144 cancels in problems of this type.

Work done by an expanding gas or vapour. Suppose a gas or vapour enters a cylinder and acts on a piston of area 1 sq. ft. with a gauge pressure of p lb. per sq. ft. If the piston is imagined to be air-tight and the other side open to the atmosphere, then the **back pressure** will be atmospheric. That is, the pressure opposing motion is atmospheric. The work done, if the expansion is resisted by a force along the piston rod, in a distance represented by BC (Fig. 26), is force × distance $= p \times 1$ sq. ft. × BC. This is represented by the area AFCB, and it will be noticed that the *work done is equal to the constant pressure in lb. per sq. ft. multiplied by the volume swept by the piston.* The pressure p has been maintained by new vapour entering the cylinder. Now suppose the vapour supply is cut off, then what is in the cylinder will expand and force the piston to the left, the pressure falling as the volume increases. If the expansion is assumed to be isothermal or according to Boyle's Law, the relation between pressure and volume will be represented by the hyperbola or isothermal CHD. The amount of work done by the movement FG of the piston will be average pressure × piston area × FG, which is represented by the area CHGF. Similarly, if the piston stops at E the work done is given by the area BCHDEFA, or the area of the pressure volume diagram represents the work done on the piston during one stroke. If the pressure had dropped

uniformly the work done would have been shown by the area BCJDEA.

Heat has always to be added to a vapour during isothermal expansion. If the expansion occurs so quickly that no heat is received from or given to external sources the expansion is called **adiabatic** (see Fig. 26, line CKL). The actual expansion curve, for

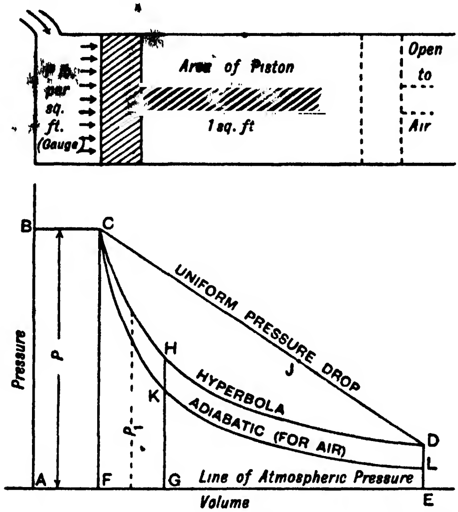


FIG. 26. Work done in a cylinder of a heat engine.

the working substance in engines, generally lies between the isothermal and the adiabatic, although nearer the latter. If the volume of the vapour in the inlet pipe is ignored,

$$\text{ratio of expansion} = \frac{\text{volume after expansion}}{\text{volume before expansion}} = \frac{AE}{AF}.$$

In the corresponding reverse operation when the working substance is compressed and its volume reduced, the ratio of compression is given by $\dfrac{\text{volume before compression}}{\text{volume after compression}}$. Thus the ratios of expansion and compression will both exceed unity.

When the expansion is adiabatic the temperature falls during the process, although no heat has left the vapour or gas other than the

heat energy in the gas which has been converted into work. In other words, the change of energy is equivalent to the external work done. During adiabatic compression the temperature of the working substance rises since external work is done on it.

The law of adiabatic expansion and compression or the equation connecting corresponding values of P and V in the pressure-volume diagram is $PV^\gamma = K$, where K is a constant depending upon the nature and quantity of the gas, and γ is the usual symbol denoting the ratio of the specific heats c_p/c_v for the gas.

For isothermal expansion and compression the equation of the curve is $PV = K$ where γ is unity, thus, $PV^\gamma = K = PV^1 = PV$. In this case since the temperature remains constant throughout the change, a quantity of heat, equivalent to the work done, must be added during expansion and deducted during compression. When a gas is expanded or compressed *very slowly* so that heat may be absorbed from the surroundings during expansion and rejected to the surroundings during compression, so as to maintain the temperature constant throughout the process, then the change may be regarded as isothermal and the pressure-volume changes follow Boyle's Law.

General law for expansion and compression curves. This law is usually written $PV^n = K$. For isothermal expansion and compression $n = 1$, and for adiabatic expansion and compression

$$n = \gamma = c_p/c_v = 1{\cdot}41$$

for air and 1·26 for steam at 100° C. and atmospheric pressure due to 30 in. of mercury. Actually n may have any value, but for the working substances generally used, the range is from 0·9 up to 1·5. Fig. 27 shows how the value of n affects the expansion curve in a number of cases; the same initial conditions of P and V have been taken for each so that a comparison can be made. When $n = 0$, the expansion curve is a straight line parallel to the axis of V, that is, expansion at constant pressure. The other extreme case shown, when $n = 2$, illustrates the inverse square law, that is, expansion such that the pressure is always inversely proportional to the square of the volume.

Fig. 28 shows in a similar way how the value of n in $PV^n = K$

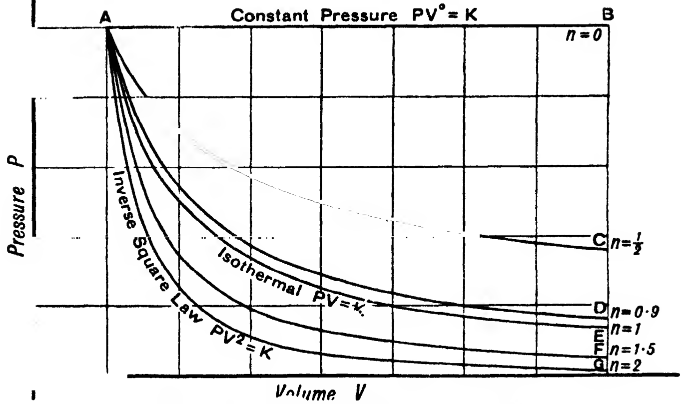


FIG. 27. $PV^n = K$, expansion curves.

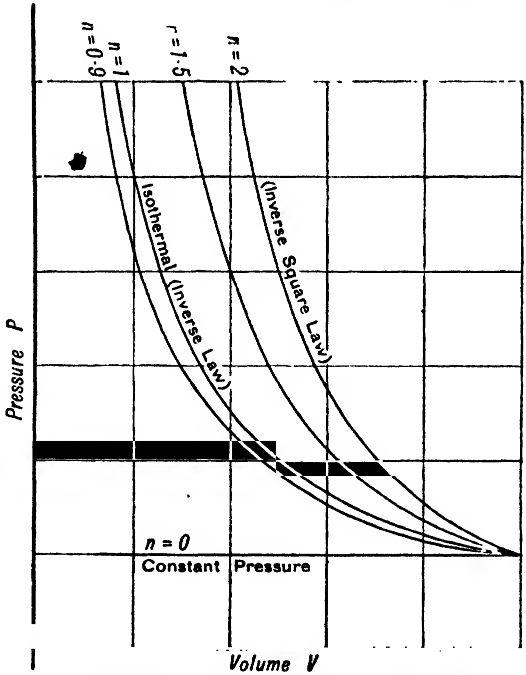


FIG. 28. $PV^n = K$, compression curves.

alters the shape of the compression curve. As before, an arbitrary point has been chosen to represent the initial values of P and V; *while the extreme cases of $n=0$ and $n=2$ are shown.*

In calculations involving $PV^n=K$, it is generally more convenient to employ the form $P_1V_1^n=K=P_2V_2^n$, the values of P_1 and P_2 being absolute pressures in the same units.

Example 1. *3 cu. ft. of gas originally at a pressure of 200 lb. per sq. in. abs. expand (a) isothermally, (b) adiabatically and (c) according to the law $PV^{1\cdot5}=K$, until a final volume of 15 cu. ft. is obtained. Calculate the final pressure in each case and the expansion ratio. Take γ as 1·4.*

Initial conditions, $V_1=3$ cu. ft. $P_1=200$ lb. per sq. in.

Final conditions, $V_2=15$ cu. ft. P_2 is required.

(*a*) Isothermal expansion, as curve AE, Fig. 27.

$$P_1V_1=P_2V_2, \quad \therefore\ P_2=P_1V_1/V_2=200\times\frac{3}{15}=\mathbf{40\ lb.\ per\ sq.\ in.}$$

(*b*) Adiabatic expansion.

$$P_1V_1^\gamma=P_2V_2^\gamma \text{ or } P_2=\frac{P_1V_1^\gamma}{V_2^\gamma}=P_1\left(\frac{V_1}{V_2}\right)^\gamma=200\times\left(\frac{1}{5}\right)^{1\cdot4}=\frac{200}{5^{1\cdot4}}$$

$$=\mathbf{21\cdot01\ per\ sq.\ in.}$$

Log 200 = 2·3010

1·4 log 5 = 0·9786

Difference = $\underline{1\cdot3224}$ = log 21·01

(*c*) Expansion according to the law $PV^{1\cdot5}=K$, as curve AF, Fig. 27.

$$P_1V_1^{1\cdot5}=P_2V_2^{1\cdot5} \text{ or } P_2=P_1\left(\frac{V_1}{V_2}\right)^{1\cdot5}=200\left(\frac{1}{5}\right)^{1\cdot5}=\frac{200}{5^{1\cdot5}}$$

$$=\mathbf{17\cdot88\ lb.\ per\ sq.\ in.}$$

Log 200 = 2·3010

1·5 log 5 = 1·0485

Difference = $\underline{1\cdot2525}$ = log 17·88

$$\text{Also } r=\text{expansion ratio}=\frac{15 \text{ cu. ft.}}{3 \text{ cu. ft.}}=\mathbf{5.}$$

Example 2. *A given mass of air has a volume of 2 cu. ft. when its absolute pressure is 220 lb. per sq. in. and its temperature 160° C.*

(*a*) *Calculate its new temperature and the work done when it expands to a volume of 6 cu. ft. while its pressure remains constant.*

(*b*) *Calculate the final temperature if the pressure of the gas falls to 25 lb. per sq. in. absolute while the volume remains at 2 cu. ft. What would be the work done, if any, in this case?*

(*a*) Initial conditions :

$P_1=220$ lb. per sq. in. absolute.

$V_1=2$ cu. ft. $T_1=160°+273°=433°$ C. abs.

Final conditions :

$P_2 = P_1 = \text{const.} \quad V_2 = 6$ cu. ft. $\quad T_2$ is required.

Then $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$ becomes $\frac{2}{433} = \frac{6}{T_2}$, or $T_2 = 1299^\circ$ C. abs.

$= 1299^\circ - 273^\circ = \mathbf{1026^\circ\ C.}$

Work done = constant pressure × change of volume (see p. 74)

$= 220 \times 144 \times (6 - 2) = \mathbf{126{,}720\ ft.\ lb.}$

(*b*) Initial conditions as in (*a*).

Final conditions : $P_2 = 25$ lb. per sq. in. abs., $V_2 = 2$ cu. ft., T_2 is required.

In this case, $\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$ becomes $\frac{220}{433} = \frac{25}{T_2}$ or $T_2 = 49{\cdot}2^\circ$ C. abs.

$= 49{\cdot}2^\circ - 273^\circ = \mathbf{-\,223{\cdot}8^\circ\ C.}$

In this case no work will be done, since there has been no change of volume.

Example 3. *In a gas engine the volume and the pressure at the commencement of expansion are respectively* 0·14 *cu. ft. and* 320 *lb. per sq. in. Find the volume when the pressure has dropped to* 50 *lb. per sq. in. if the expansion is* (*a*) *isothermal,* (*b*) *adiabatic, or* (*c*) *according to the law* $PV^{1\cdot3} = K$. *Take* γ *as* 1·4 *for adiabatic expansion.*

Initial conditions : $P_1 = 320$ lb. per sq. in. $\quad V_1 = 0{\cdot}14$ cu. ft.

Final conditions : $P_2 = 50$ lb. per sq. in. $\quad V_2$ is required.

(*a*) Isothermal expansion.

$P_1 V_1 = P_2 V_2$, or $V_2 = P_1 V_1 / P_2 = 320 \times 0{\cdot}14/50 = \mathbf{0{\cdot}896\ cu.\ ft.}$

(*b*) Adiabatic expansion.

$$P_1 V_1^{\gamma} = P_2 V_2^{\gamma} \text{ or } V_2^{\gamma} = \frac{P_1}{P_2} V_1^{\gamma} = \frac{320}{50} \,.\, 0{\cdot}14^{1\cdot4} = 6{\cdot}4 \times 0{\cdot}14^{1\cdot4}.$$

Thus, $V_2^{1\cdot4} = 6{\cdot}4 \times 0{\cdot}14^{1\cdot4}$, and taking logarithms of each side of the equation,

$$1{\cdot}4 \log V_2 = \log 6{\cdot}4 + 1{\cdot}4 \log 0{\cdot}14.$$

Divide through by 1·4,

$$\log V_2 = (0{\cdot}8062 \div 1{\cdot}4) + \bar{1}{\cdot}1461$$
$$= 0{\cdot}5759 + \bar{1}{\cdot}1461 = \bar{1}{\cdot}7220\,;$$
$$\therefore\ V_2 = \mathbf{0{\cdot}5272\ cu.\ ft.}$$

(*c*) Expansion according to $PV^{1\cdot3} = K$.

$$P_1 V_1^{1\cdot3} = P_2 V_2^{1\cdot3} \text{ or } V_2^{1\cdot3} = \frac{P_1}{P_2} V_1^{1\cdot3} = \frac{320}{50} \times 0{\cdot}14^{1\cdot3} \text{ or } 6{\cdot}4 \times 0{\cdot}14^{1\cdot3}.$$

Taking logarithms of each side,

$$1{\cdot}3 \log V_2 = \log 6{\cdot}4 + 1{\cdot}3 \log 0{\cdot}14.$$

Dividing through by 1·3,

$$\begin{aligned}\log V_2 &= (\log 6{\cdot}4 \div 1{\cdot}3) + \log 0{\cdot}14\\ &= 0{\cdot}8062 \div 1{\cdot}3 + \bar{1}{\cdot}1461\\ &= 0{\cdot}6202 + \bar{1}{\cdot}1461 = \bar{1}{\cdot}7663.\end{aligned}$$

$$\therefore \; V_2 = 0{\cdot}5838 \text{ cu. ft.}$$

Example 4. *Find the temperature and pressure at the end of compression for a Diesel engine if the initial conditions are* 100° *F. and pressure* 14·5 *lb. per sq. in. abs., compression ratio* 14. *Compression curve law,* $PV^{1{\cdot}35} = K$.

Initial conditions :

$P_1 = 14{\cdot}5$ lb. per sq. in., $V_1 = 14$ units, $T_1 = 460° + 100° = 560°$ F. abs.

Final conditions : P_2 is required, $V_2 = 1$ unit, T_2 is required.

The value of P_2 must first be determined from

$$P_1 V_1^{1{\cdot}35} = P_2 V_2^{1{\cdot}35} \text{ or } P_2 = P_1\left(\frac{V_1}{V_2}\right)^{1{\cdot}35} = 14{\cdot}5 \times \left(\frac{14}{1}\right)^{1{\cdot}35}$$

$$= 511{\cdot}2 \text{ lb. per sq. in. abs.}$$

To find T_2 use the relationship, $\dfrac{P_1 V_1}{T_1} = \dfrac{P_2 V_2}{T_2}$,

which applies since the mass of gas is unchanged.

$$\therefore \; T_2 = \frac{P_2}{P_1} \cdot \frac{V_2}{V_1} \cdot T_1 = \frac{511{\cdot}2}{14{\cdot}5} \times \frac{1}{14} \times 560 = 1410° \text{ F. abs.}$$

$$\therefore \text{ final temperature} = 1410° - 460° = 950° \text{ F.}$$

Properties of steam. Steam is the vapour of water, and when pure and dry is invisible. Cooling action causes particles of steam to condense and form globules of water, and it is the minute condensed particles of water which, being suspended in a steam jet, make it visible. Steam in this condition is spoken of as **wet steam.**

Suppose 1 lb. of pure water at 0° C. is enclosed in a cylinder fitted with a steam-tight piston of negligible weight. To raise this water to boiling point will require about $1 \times 1 \times 100 = 100$ C.H.U. if the specific heat is assumed equal to unity. This heat is called

sensible heat (see Fig. 29), since the heat supplied causes a rise in temperature—in this case 100° C. Owing to the variation of the specific heat of water with the temperature the actual sensible heat is 100·159 C.H.U., but as the variation is small it is often neglected. This figure, it must be remembered, is only correct if the pressure is atmospheric. If more heat is applied to this 1 lb. of water at 100° C. the piston will rise, due to the formation of steam, but there is no change of temperature until all the water is converted into steam. This heat which liquids require to vaporise them is called **latent**

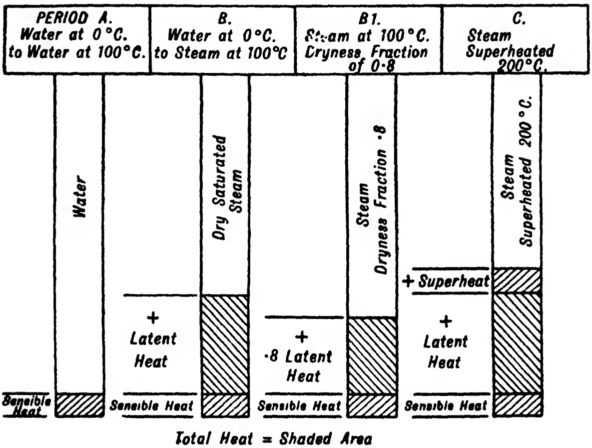


FIG. 29. Total heat of water steam at atmospheric pressure.

heat. To turn 1 lb. of water into steam at a pressure of 30 in. of mercury requires 539·3 C.H.U. (whereas to change 1 lb. of ice into water at 0° requires only 80 C.H.U.). The steam now occupies 26·79 cu. ft., as compared with 0·016 cu. ft. in the case of water (Fig. 29, B). Should the steam contain water particles, less heat has been absorbed, and the steam is said to possess a **dryness fraction** of 0·8 if 80% by weight is steam and 20% water. Steam is said to be dry saturated if it is in contact with the water from which it is generated, and its dryness fraction is unity. The **total heat of dry** saturated steam = sensible heat + latent heat = 100 + 539·3 or 639·3 C.H.U. If the dryness fraction is 0·8, the total heat of the wet steam (Fig. 29 B1) becomes $100 + 0{\cdot}8 \times 539{\cdot}3$ or 531·4 C.H.U.

When heat is given to dry saturated steam in a *separate vessel* at constant pressure, the steam is said to be **superheated.** Taking the specific heat of steam as 0·5 and the temperature being raised to 300° C., then $1 \times 0{\cdot}5 \times 200$ or 100 C.H.U. will be required. The total heat now becomes (Fig. 29, c) $100 + 539{\cdot}3 + 100$ or 739·3 C.H.U. The shaded portions of the diagrams in Fig. 29 illustrate the relative amounts of heat required under the headings of sensible, latent and superheat for steam raised at atmospheric pressure.

The sum of sensible + latent + superheat (if any) for 1 lb. of steam produced from water at 0° C. is called the **total heat of steam**, and the figure varies with the pressure at which the steam is generated. As the pressure is raised it is found that (1) the boiling point is raised, (2) the sensible heat required increases, (3) the latent heat decreases, (4) the total heat increases, (5) the specific volume in cu. ft. per lb. decreases. These results have been determined after careful experiments, and the results have been embodied in Callendar's Steam Tables, p. 100.

The temperature at which evaporation takes place in a boiler depends upon the pressure inside it, and it must be remembered that, *for a given pressure, saturated steam can only exist at one temperature.* This rigid connection between the pressure and temperature of a vapour in contact with its liquid enables tables or graphs to be constructed giving the temperature and corresponding pressure.

The boiling point of water at a given pressure is called the **saturation temperature** at that pressure, because it is the temperature at which saturated steam is produced. Sometimes the boiling point is referred to as the **evaporation temperature.** The maximum pressure in a boiler at which steam is generated is fixed by the spring or dead weight load on the boiler safety valve. In boilers the boiling point of the water will be above 100° C., but it will be below this temperature in de-aerators and condensers, because the pressure is below atmospheric.

From the foregoing it will be seen that the important properties of steam include its pressure and temperature, specific volume, sensible heat, latent heat, dryness fraction, superheat and total heat. A knowledge of these properties is essential to the steam engine designer, the steam user, and to the student studying heat engines.

It is important that the following points be realised in making calculations of steam quantities.

(1) The **sensible heat** at any given pressure, denoted by h and sometimes referred to as the total heat of water or as liquid heat, should preferably be taken from tables. By assuming the specific heat of water is constant and remains unity, the change of sensible heat can be calculated approximately by multiplying the mass of the water by the change of temperature. A change in sensible heat can only be brought about by a change of temperature. The expansion of the water while receiving sensible heat is neglected in elementary work.

(2) The **latent heat of vaporisation** of steam, denoted by L, is always absorbed by the steam at constant temperature when steam is being generated from water. Similarly when steam is being condensed, this latent heat is given up at constant temperature. Thus, since one depends on the other, the pressure and temperature will remain constant during the application and rejection of latent heat in steam power plants. The actual temperature of boiling depends on the degree of purity of the water as well as the pressure upon the water surface. As soon as the boiling point is reached, any further heat received by the water is absorbed as latent heat, and steam begins to be produced. When the steam generated has absorbed the maximum latent heat and consequently there is no water in suspension, the steam is variously called *dry*, *dry saturated*, or sometimes just *saturated steam*. The student should realise that water will not boil so long as its temperature is below that corresponding to the boiling point at that pressure, and more sensible heat will be necessary to raise the temperature to that boiling point which corresponds to the pressure.

(3) **Superheated steam.** When w lb. of dry saturated steam is heated at constant pressure in a separate vessel, that is, not in contact with its water of generation, its volume increases and the steam becomes superheated or supersaturated, absorbing a quantity of heat equal to

$$w \times c_p \times \text{degree of superheat},$$

where c_p is the specific heat at constant pressure.

The **degree of superheat** is the difference between the temperature of steam generation in the boiler and the final temperature in the superheater. In every calculation on heat quantities of superheated steam, it must be remembered that the specific heat of superheated steam varies considerably with the temperature and pressure. Care must therefore be taken to obtain the correct mean value for the specific heat c_p. It is more satisfactory to work from steam tables or steam charts if these are available, because with these the variation of specific heat has been considered and allowed for.

Callendar's equation, in an approximate form, is very useful for determining the specific volume V of superheated steam. It is

$$V = \frac{1 \cdot 2464}{P}(H - 835),$$

where V = volume in cu. ft. per lb., H = total heat in B.Th.U. per lb., P = pressure of steam in lb. per sq. in. absolute.

(4) In finding the total heat H of saturated steam where x is the dryness fraction, the value L taken from tables must be multiplied by x. Thus $H = h + xL$, where

$$x = \frac{\text{latent heat possessed by 1 lb. of steam}}{\text{latent heat of 1 lb. of dry steam at the same pressure}}.$$

If the degree of superheat is known the total heat of superheated steam may be taken from steam tables when the pressure is also known. A graph is a useful device for obtaining intermediate values not given in steam tables. Thus if the particular value of sensible heat, latent heat, or total heat of any quality of steam is not given in the steam tables, the value required can be obtained by interpolation from a graph drawn by plotting a number of known points, in the neighbourhood of the one required, and drawing a fair curve through them.

Expt. 19. **Variation of boiling point with pressure.**

Object. *To show that the boiling point of water increases with the pressure.*

Apparatus. Arrange a flask of water with a bored stopper, one boring containing a thermometer and the other a bent tube leading, as shown in Fig. 30, to a reservoir of mercury. As steam is formed the pressure above the water is increased, and this increase of pres-

sure may be measured by the mercury height above the bottom of the tube.

METHOD OF PROCEDURE. Heat the water in the flask to a condition of boiling, and then by adding mercury to the reservoir obtain a series of results for the boiling point with different depths of mercury, that is, different gauge pressures of steam formation.

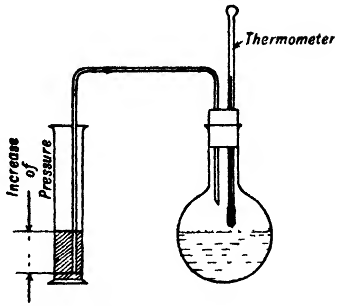


FIG. 30. Variation of boiling point.

OBSERVATIONS.

Increase of pressure in. of mercury					
Temp. of boiling, °C.					

EXPT 20. OBJECT. *To show the connection between the pressure and temperature of saturated steam.*

APPARATUS. A Marcet boiler can be used for this experiment. It is provided with (1) a pressure gauge for reading pressures above atmospheric, (2) a thermometer pocket containing mercury to ensure good contact with the interior of the boiler, (3) a lever safety valve, (4) a tripod for supporting the apparatus, (5) a steam cock and connections for conducting other experiments. The cover is secured by suitable nuts and bolts to make a steam-tight joint. See Fig. 31.

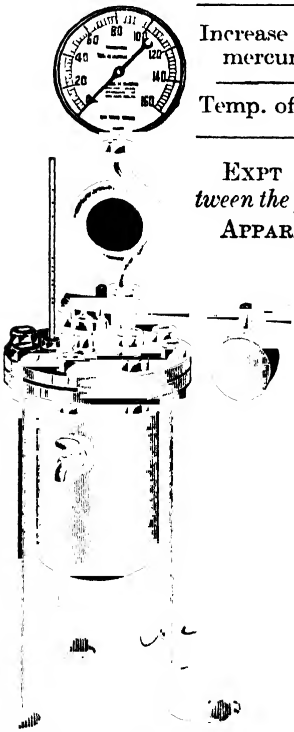


FIG. 31. Marcet boiler.
(*Messrs. G. Cussons, Ltd.*)

METHOD OF PROCEDURE. First heat the boiler, half-filled with water, by means of a bunsen burner until the gauge pressure is about 15 lb. per sq. in., and lift the safety valve to allow the air above the water to be driven out and be replaced by steam. Then allow the boiler to cool and the pressure to drop to atmospheric pressure. This ensures as

far as possible the whole apparatus being at the same temperature before readings are taken. Now heat the boiler and tabulate values of gauge pressure and temperature up to, say, 120 lb. per sq. in., remove the bunsen and, as the apparatus cools, read the temperatures corresponding to the pressures previously recorded. For pressures and temperatures below atmospheric, a glass U tube containing mercury could be connected by rubber tubing to the steam cock. This connection must be made at the moment when steam is issuing freely from the cock and the source of heat has just been removed. Then as the apparatus cools, absolute pressures can be read by subtracting the difference in mercury levels from the height of the mercury barometer. The observations can be tabulated under the headings shown.

OBSERVATIONS. Barometric pressure = 15 lb. per sq. in.

Gauge pressure, lb. per sq. in.	Absolute pressure, lb. per sq. in.	Temperature (heating) °C.	Temperature (cooling) °C.	Average temperature (heating and cooling)
10	25	114	118	116
20	35	124	127	125·5
30	45	133	135	134
40	55	141	142	141·5
50	65	146	148	147
60	75	152	152	152
70	85	157	157	157
80	95	161	161	161
90	105	166	164	165
100	115	169·5	168·5	169
110	125	173	172	173
120	135	176 5	-	176 5

NOTE. The results obtained in this experiment are necessarily approximate. Recourse must be made to Standard Steam Tables for accurate results.

Example 1. *If the pressure inside a boiler is* 410 *lb. per sq. in. abs., at what temperature will the water boil? If the temperature falls to* 420·4° *F., what will be the new steam pressure?*

From steam tables, p. 100, saturation temperature at 410 lb. per sq. in. is 447·2° F.

Also pressure corresponding to saturation temperature 420·4° F. is 420 lb. per sq. in.

Example 2. *The feed water supplied to a boiler with a working pressure of 120 lb. per sq. in. abs. has a temperature of 120° F. What amounts of sensible and latent heat must be supplied within the boiler to produce 1 lb. of dry steam? At what pressure would the water boil at 120° F.?*

Saturation temperature for 120 lb. per sq. in. = 341·3° F. from steam tables.

Sensible heat (measured above 32° F.) from tables is 312·5 B.Th.U. per lb.

Sensible heat measured above 120° F. is (312·5 − 120 + 32) = **224·5 B.Th.U. per lb.**

Assuming the specific heat of water as constant and equal to unity, the sensible heat above 120° F. is, per lb.,

$$1 \times (341 - 120) \times 1 = \mathbf{221{\cdot}3\ B.Th.U.}$$

Latent heat required per lb. at 120 lb. per sq. in. from tables = **881·8 B.Th.U.**

Fig. 32 shows a graph obtained by plotting saturation temperatures and pressures. From the graph it will be seen that the water will boil at **1·68 lb. per sq. in. abs.**, when at 120° F.

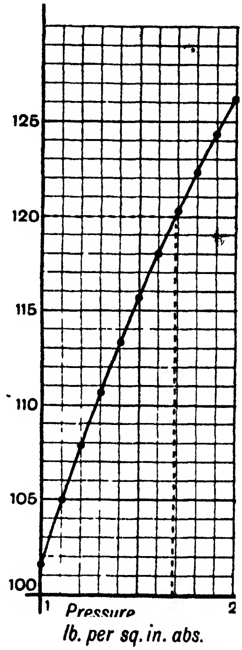


FIG. 32. Graph for Ex. 2.

Example 3. *If 900 lb. of steam per hour enters a condenser where the pressure is 1 lb. per sq. in. abs., determine the temperature in the condenser and the amount of latent and sensible heat abstracted per hour. The condensate or condensed steam has a temperature of 26·4° C. when pumped from the condenser.*

The temperature in the condenser is that corresponding to a pressure of 1 lb. per sq. in., or from tables, **38·73° C.**

Sensible heat per lb. at 38·73° C. or temperature of condensation is from tables 38·62 C.H.U.

This is the sensible heat per lb. of steam as condensed.

Sensible heat in condensate at 26·4° C. (from tables) = 26·33 C.H.U. per lb.

Sensible heat extracted in condenser = 38·62 − 26·33 C.H.U. per lb.
= **12·29 C.H.U. per lb.**

Sensible heat extracted per hour = 900 × 12·29 C.H.U.
= **11,061 C.H.U.**

Latent heat extracted per lb. = latent heat corresponding to 1 lb. per sq. in. abs. from tables $= H - h = 612{\cdot}46 - 38{\cdot}62$ C.H.U.
$= 573{\cdot}84$ C.H.U.

Latent heat extracted per hour $= 900 \times 573{\cdot}84$ C.H.U.
$=$ **516,456 C.H.U.**

Example 4. *Find the heat necessary to raise 1 lb. of feed water at 50° C. to dry saturated steam at 350 lb. per sq. in. (absolute). What heat would be necessary if the dryness fraction were 0·96.? What is the volume of the steam in each case ?*

From tables, total heat at 350 lb. per sq. in. $= 672{\cdot}8$ C.H.U.
Initial heat above 0° C. in feed water $= 50$ C.H.U.
Heat necessary, by difference $=$ **622·8 C.H.U.**
Specific volume (from tables) $=$ **1·336 cu. ft. per lb.**

For dryness fraction of 0·96,
total heat = sensible heat + 0·96 × latent heat
$= 227{\cdot}8 - 50 + 0{\cdot}96 \times 445$
$= 227{\cdot}8 - 50 + 427{\cdot}2 =$ **605 C.H.U.**

Volume of wet steam
$= 0{\cdot}96 \times 1{\cdot}336$
$=$ **1·283 cu. ft. per lb.**, if volume of water is neglected.

Example 5. *Find the heat necessary to superheat the steam in the last question to 350° C. at constant pressure if the specific heat of steam is 0·58 and remains constant. What is then the total heat of the steam ?*

From tables, dry saturated steam at 350 lb. per sq. in. absolute has a temp. of 222·1° C.

Degree of superheat required $= 350° - 222{\cdot}1° = 127{\cdot}9°$ C.
Heat required for 1 lb. $= 1 \times 0{\cdot}58 \times 127{\cdot}9 =$ **74·2 C.H.U.**
Total heat required per 1 lb. $= 672{\cdot}8 + 74{\cdot}2 =$ **747 C.H.U.**

Example 6. *1 lb. of steam at 350° C. and 400 lb. per sq. in. (gauge) is cooled in a cylinder until its dryness fraction is 0·75 and its pressure 40 lb. per sq. in. (absolute). What is the final temperature and volume of the steam ? Assume specific heat of superheated steam as 0·62. How much heat has been abstracted from the steam ?*

From tables, final temp. at 40 lb. per sq. in. $=$ **130·67° C.**
Volume of steam $= 0{\cdot}75 \times 10{\cdot}5$ $=$ **7·875 cu. ft. per lb.**

Temperature of dry saturated steam at 400 lb. per sq. in. (gauge) $= 231{\cdot}3°$ C.
∴ degree of superheat $= 118{\cdot}7°$ C.

Total heat of steam initially $= 673 \cdot 5 + 0 \cdot 62 \times 118 \cdot 7 = 673 \cdot 5 + 73 \cdot 59$
$= 747 \cdot 1$ C.H.U.

Total heat of steam finally $= 131 \cdot 08 + \frac{3}{4} \times 519 \cdot 87 = 521$ C.H.U.

Heat abstracted $= 747 \cdot 1 - 521 =$ **226·1 C.H.U. per lb.**

Example 7. *20 lb. of saturated steam at 200 lb. per sq. in. (absolute) and dryness fraction 0·9 is blown into a tank containing 500 lb. of water at 25° C. Find the final temperature of the water.*

Total heat of 1 lb. of steam from tables $= 197 \cdot 49 + 0 \cdot 9 \times 471 \cdot 2$
$= 621 \cdot 6$ C.H.U.

Then neglecting losses and assuming final temp. is $t°$ C.:

Heat gained by water heat lost by steam.

$$500 \times 1 \times (t - 25) = 20 \times (621 \cdot 6 - t).$$

$$500t - 12{,}500 = 12{,}432 - 20t.$$

$$t = \frac{24{,}932}{520} = \mathbf{47 \cdot 9° \ C.}$$

Example 8. (*a*) *Steam is supplied to an engine cylinder of 20 in. dia. at 180 lb. per sq. in. abs. What weight of steam will be drawn into the cylinder during a movement of 1 foot of the piston if the dryness fraction of the steam is 0·97?*

(*b*) *What weight of superheated steam at the same pressure and 200 Fahr. degrees of superheat will be required to fill the same volume? Use* $V = 1 \cdot 2464(H - 835)/P$.

(*a*) Specific volume of steam at 180 lb. per sq. in. abs. from tables
$= 2 \cdot 536$ cu. ft. per lb.

If 97% dry, volume $= 2 \cdot 536 \times 0 \cdot 97 = 2 \cdot 46$ cu. ft. per lb.

Volume in cylinder $= \dfrac{\pi \times 10^2}{144} \times 1 = 2 \cdot 182$ cu. ft.

$\therefore$ Wt. of steam in cylinder $= \dfrac{2 \cdot 182}{2 \cdot 46} \times 1$ lb. $=$ **0·887 lb.**

(*b*) Total heat of superheated steam H at 180 lb. per sq. in. abs. with 200 Fahr. degrees of superheat from Callendar's abridged Steam Tables
$= 1313 \cdot 2$ B.Th.U. per lb.

$P = 180$ lb. per sq. in.

$$V = 1 \cdot 2464(1313 \cdot 2 - 835)/180$$
$$= 1 \cdot 2464 \times 478 \cdot 2/180 = 3 \cdot 31 \text{ cu. ft. per lb.}$$

$\therefore$ Wt. of steam in cylinder $= \dfrac{2 \cdot 182}{3 \cdot 31} \times 1 =$ **0·659 lb.**

Example 9. *In an experiment to estimate approximately the dryness fraction of steam, steam was blown into a known weight of water in a copper calorimeter. The following observations were made :*

Wt. of copper calorimeter = 95·4 *gm.* *Temp. of cold water* = 15° C.
Wt. of calorimeter + water = 296·4 *gm.*
Temp. of boiler steam = 229·3° *C.*
Wt. of calorimeter + water + condensed steam = 306·7 *gm.*
Pressure of boiler steam = 400 *lb. per sq. in. abs.*
Specific heat of copper = 0·095.
Final temp. of water = 44·8° *C.*
Assume that there are no heat losses.

Water value or water equivalent of calorimeter

$$= 0{\cdot}095 \times 95{\cdot}4 = 9{\cdot}06 \text{ gm.}$$

Wt. of cold water in calorimeter	$= 296{\cdot}4 - 95{\cdot}4$	$= 201$ gm.
Equivalent wt. of water	$= 201 + 9{\cdot}06$	$= 210{\cdot}06$ gm.
Wt. of steam condensed	$= 306{\cdot}7 - 296{\cdot}4$	$= 10{\cdot}3$ gm.

Then the heat lost by 10·3 gm. of steam above a datum of 44·8° C. will equal the heat gained by 210·06 gm. of water in being raised from 15° C. to 44·8° C.

Heat gained by water $= 210{\cdot}06 \times (44{\cdot}8 - 15) = 6259$ gram calories.

$\therefore$ heat lost by 1 gm. of steam $= \dfrac{6259}{10{\cdot}3} = 607{\cdot}7$ gram calories.

Thus the steam in the boiler possesses 607·7 gram calories per gm. above 44·8° C. Measured above 0° C. the heat content of the steam would be $607{\cdot}7 + 44{\cdot}8$ nearly $= 652{\cdot}5$ gram calories.

From tables, heat in 1 lb. of dry steam at 400 lb. per sq. in. abs.

$$= 673{\cdot}4 \text{ C.H.U.}$$

$\therefore$ total heat in 1 gm. of dry steam $= 673{\cdot}4$ gram calories.

Thus the boiler steam has a shortage of $673{\cdot}4 - 652{\cdot}5$ or 20·9 gram calories as compared with dry saturated steam.

Latent heat of wet boiler steam = latent heat of dry steam − 20·9

$$= 437{\cdot}5 - 20{\cdot}9 = 416{\cdot}6,$$

the units being gram calories per gm. in each case.

$\therefore$ the dryness fraction of the boiler steam

$$= \frac{416{\cdot}6}{437{\cdot}5} \times 100 = 95{\cdot}2\%.$$

Expt. 21, which follows, describes a method of determining the dryness fraction of steam by mechanically separating the water particles from the steam. This is most effectively carried out by fitting vanes within the separating calorimeter, so that the steam is given a whirling or spiral motion whereby the water particles are flung by centrifugal force against the sides of the vessel, whence they drain and can be weighed.

In Expt. 22 the dryness fraction is determined by a throttling calorimeter in which the steam is allowed to expand without doing external work by escaping through a small aperture. The internal energy of the steam thus remains constant, but as the pressure has fallen the total heat necessary for dry steam also has fallen, and the excess heat possessed by the steam goes to evaporating its moisture and to superheating the steam.

Where a throttling calorimeter is used without a separating calorimeter, an estimate of the dryness fraction can only be made if the condition of the steam after throttling is either saturated or superheated. For this reason a throttling calorimeter is only effective with steam having a dryness fraction of over 0·93.

Expt. 23 deals with an experimental method of ascertaining some of the properties of superheated steam.

EXPT. 21. **The separating calorimeter.**

OBJECT. *To find the dryness fraction of steam, using a separating calorimeter only.*

APPARATUS. Fig. 33 shows a diagram of a separating calorimeter, often fitted with vanes to give the steam a whirling motion, in which steam is admitted through a stop valve to an internal short tube contained in an outer casing or separating chamber. The water in suspension falls into the base of this chamber, and can be drawn off through the water tap. Its level is shown by the water gauge glass attached to the wall of the separating chamber. The steam leaves the separating chamber, and is carried to a coil condenser of sufficient area to condense completely the steam supply to the calorimeter.

METHOD OF PROCEDURE. Pass steam through the calorimeter until the temperature of the separating chamber has reached that of the steam. Thoroughly drain this chamber, and allow a passage of steam for some time into a weighed quantity of water surround-

ing the condenser. This steam will then give up its moisture in the separating chamber, and the total amount of supply steam will be the weight of condensed steam in the condenser together with the

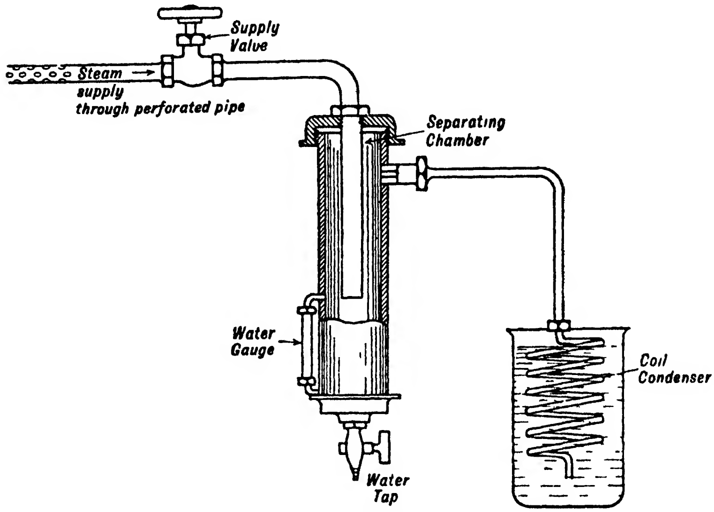


FIG. 33. Separating calorimeter.

water trapped in the separating chamber. Obtain the weight of the condensate by finding the weight added to that of the cooling water. Drain off the trapped moisture and weigh this, then if

W = weight of cooling water,

W_1 = weight of cooling water + condensate,

$W_1 - W$ = weight of condensate,

W_2 = weight of trapped water,

$W_2 + (W_1 - W)$ = weight of wet steam supplied.

$$\text{Dryness fraction} = \frac{\text{weight of steam supplied} - \text{weight of moisture}}{\text{weight of steam supplied}}$$

$$\frac{W_2 + (W_1 - W) - W_2}{W_2 + (W_1 - W)}$$

$$\frac{\mathbf{W_1 - W}}{\mathbf{W_2 + (W_1 - W)}} \text{ or } \frac{\textbf{weight of condensate}}{\textbf{weight of steam supplied}}.$$

EXPT. 22. **The throttling calorimeter.**

OBJECT. *To determine the dryness fraction of steam when this steam is not less than* 93% *dry.*

APPARATUS. For the purpose of this experiment a throttling calorimeter (Fig. 34) is employed. The steam is admitted through a large number of holes in a supply pipe A, and is throttled by passing it through the narrow aperture or opening of the screw down valve B. This produces a fall of pressure when the steam is allowed to expand into the chamber C, in consequence of which heat is given

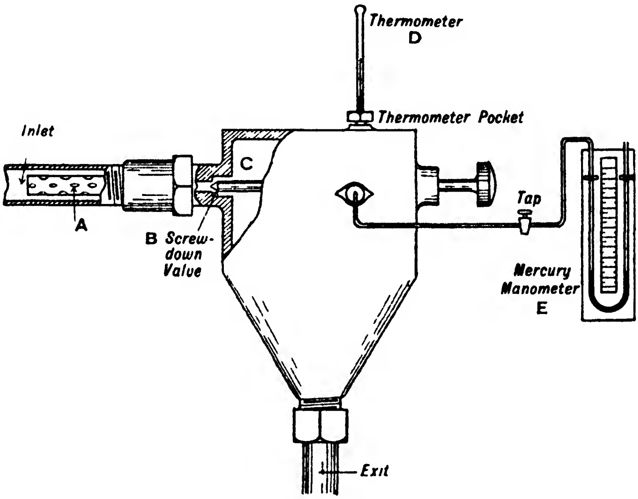


FIG. 34. Throttling calorimeter.

up to form dry saturated or superheated steam in C. NOTE.—*This is only applicable when the dryness fraction of the supply steam exceeds* 93%, *otherwise dry saturated steam would not be obtained.* The pressure of the supply steam is measured by a pressure gauge on the supply side of the inlet A, and the temperature and pressure of the steam in C by the thermometer D and manometer E.

METHOD OF PROCEDURE. Steam is passed through the throttling valve into C and the temperatures and pressures before and after throttling noted. Then the heat given up by the pre-throttled steam is equal to the total heat of saturation and superheat after throttling. From this heat equation the dryness fraction of the steam before throttling can be deduced.

OBSERVATIONS AND DERIVED RESULTS.

Supply:

Pressure of steam in pipe $= 90$ *lb. per sq. in absolute.*
Barometer reading $= 30{\cdot}53$ in. of mercury.

After throttling:

Temperature of steam $= 119°$ C.
Pressure of steam gauge $= 6{\cdot}2$ in. of mercury.
Pressure of steam absolute $= 30{\cdot}53 + 6{\cdot}2 = 36{\cdot}73$ in.
$= 36{\cdot}73 \times 0{\cdot}49 = 18$ lb. per sq. in.

Heat quantities (from steam tables):

Latent heat per lb. at 90 lb. per sq. in. $= 498{\cdot}9$ C.H.U.
Sensible heat per lb. at 90 lb. per sq. in. $= 161{\cdot}4$ C.H.U.
Temperature of saturation at 18 lb. per sq. in. $= 105{\cdot}79°$ C.
Degree of superheat $= 119 - 105{\cdot}79 = 13{\cdot}21°$ C.
Total heat of superheated steam at 18 lb. per sq. in. and $13{\cdot}21°$ C. of superheat $= 648$ C.H.U. (from tables).

Then if x be the dryness fraction at supply,

$$x \times 498{\cdot}9 + 161{\cdot}4 = 648,$$

$$x = \frac{486{\cdot}6}{498{\cdot}9} = 0{\cdot}976,$$

that is, **97·6% dry.**

EXPT. 23. **Superheated steam.**

OBJECTS. (*a*) *To find the temperature of superheated steam at a certain pressure.*

(*b*) *To find the total heat of superheated steam.*

(*c*) *Assuming a value for the total heat of superheated steam at a given pressure, to calculate the specific heat of steam at constant pressure.*

APPARATUS. This consists of a steel drum fitted with a flue and gas burner as shown in Fig. 35. Inside the drum is several turns of solid drawn copper tubing, which forms the superheater unit. The burner gases are directed by baffles to serve the whole of the superheater unit. The inlet side of the superheater is taken out, fitted with a pressure gauge, thermometer and pocket, and lagged to the boiler supply, provision being made for connecting a throttling calorimeter between the boiler and the gauge. The outlet side is similarly lagged and fitted with (*a*) a pressure gauge, (*b*) a thermometer and pocket, (*c*) a two-way steam cock. After the cock a

union is fitted to connect the superheater unit to a coil of copper tubing, which serves as a condenser unit. This is carried into a copper calorimeter in a lagged container, fitted with an ebonite lid with stirrer and thermometer gland.

METHOD OF PROCEDURE.

(*a*) The two-way cock is set to allow the steam passing through the superheater to exhaust into the atmosphere. Then the gas burner is lit and the steam allowed to superheat at constant pressure.

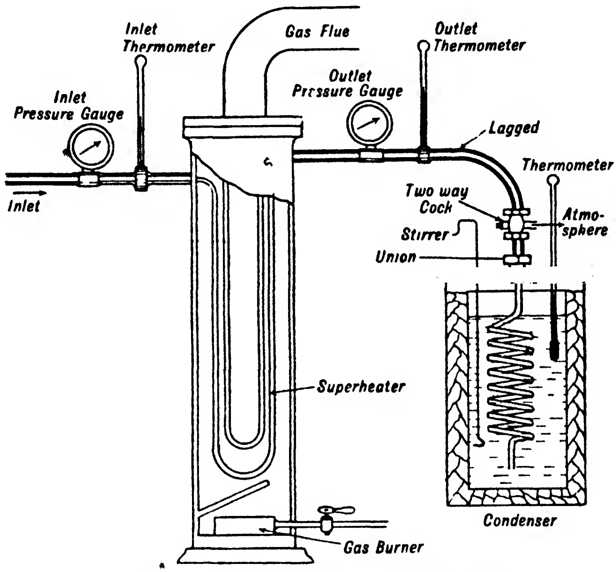


FIG. 35 Properties of superheated steam.

The condition of constant pressure is verified by readings of the inlet and outlet pressure gauges. The temperatures at inlet and outlet are then noted, and particular care is taken to see that the two-way cock is adjusted to allow the temperature at outlet to be above saturation temperature at this pressure, that is, to provide that the steam shall be superheated. Then the temperature of outlet is the temperature of superheated steam at the pressure indicated on the outlet pressure gauge.

(*b*) For this portion of the experiment the condition of the steam at entry can be taken by a throttling calorimeter, and a heat balance obtained with its condition at outlet and the heat given in the

superheater. This will convince the student that the steam is both dried and superheated in the superheater unit. Next remove the condenser coil at the unit and weigh it with the copper calorimeter. Obtain the water equivalent of this condenser unit by multiplying the weight of coil and calorimeter by the specific heat of copper. Three-quarter fill the calorimeter with water, and obtain the weight of water by weighing the calorimeter coil and water together. Fit the ebonite lid, stirrer and thermometer, and connect the condenser to the superheater unit. Light the gas burner and open the two-way cock to the atmosphere, thus allowing superheated steam to pass through the whole of the system except the condenser until the pressure gauges and thermometers give a steady reading. Next close the two-way cock to the atmosphere and pass the superheated steam into the condenser, stirring in the process, until a rise of temperature of about 20° C. occurs in the condenser water. Close the cock to the condenser and open to atmosphere, at the same time shutting off the gas supply. From the results calculate the total heat of the superheated steam by the method shown in the derived results.

(c) Use steam tables to find the total heat of steam at the temperature and pressure of outlet. From these results and the observations in section (b), calculate the specific heat of steam at constant pressure.

OBSERVATIONS AND DERIVED RESULTS.

(a) Pressure of steam at outlet $=P$ lb. per sq. in. gauge

$=P+14{\cdot}7$ lb. per sq. in. absolute.

Temperature of steam at outlet $=t°$ C.

Temperature of saturation at $P+14{\cdot}7$ lb. per sq. in. absolute $=t_1°$ C.

Temperature of superheat $=t-t_1°$ C.

(b)	Weight of condenser unit	$=W$ lb.
	Weight of condenser unit + water	$=W_1$ lb.
	Weight of water	$=W_1-W$ lb.
	Water equivalent of condenser unit	$=0{\cdot}095W$ lb.
	Temperature of outlet steam	$=T°$ C.
	Initial temperature of water in condenser	$=t°$ C.
	Final temperature of water in condenser	$=t_1°$ C.
	Weight of condenser unit + water + condensed steam	$=W_2$ lb.
	Weight of condensed steam	$=W_2-W_1$ lb.

Heat given up by steam

$$= \text{heat given to condenser unit and water}$$
$$= (W_1 - W)(t_1 - t) + 0{\cdot}095W(t_1 - t)$$
$$= (W_1 - W + 0{\cdot}095W)(t_1 - t) \text{ C.H.U.},$$

and this is given up by $W_2 - W_1$ lb. of steam.

Heat possessed by $W_2 - W_1$ lb. of steam after condensation

$$= (W_2 - W_1)t_1 \text{ C.H.U., or } t_1 \text{ C.H.U. per lb.}$$

Total heat of 1 lb. of superheated steam

$$= \frac{(\mathbf{W_1 - W + 0{\cdot}095W})(\mathbf{t_1 - t})}{\mathbf{W_2 - W_1}} + \mathbf{t_1} \textbf{ C.H.U.}$$

(*c*) If $T°$ C. is the temperature of the outlet steam at P lb. per sq. in. absolute, then from steam tables:

Total heat of superheat $= H$ C.H.U.

Total heat of saturation $= H_1$ C.H.U.

Let S be the specific heat of steam and t_s be the temperature of saturation at P lb. per sq. in. absolute.

Then $H = H_1 + (T - t_s)S$ in C.H.U.

From section (*b*), $H = \dfrac{(W_1 - W + 0{\cdot}095W)(t_1 - t)}{W_2 - W_1} + t_1$

$$\therefore \frac{(W_1 - W + 0{\cdot}095W)(t_1 - t)}{W_2 - W_1} + t_1 = H_1 + (T - t_s)S.$$

Hence S can be calculated.

Measurement of high temperature. A **pyrometer** is an instrument for measuring high temperatures. The **pressure gauge pyrometer** is a simple and efficient type. Its action depends upon the fact that, when a liquid is in contact with its vapour in a closed vessel, the temperature of the vapour will always be the same for any given pressure. Therefore if the pressure is recorded, then the temperature can be found. If the range of pressures and corresponding temperatures are known for a liquid, then this liquid can be used as a working substance for the pyrometer. For example, if water were used, the data from steam tables would permit the dial of the pressure gauge to be marked in temperatures as well as pressures

The essential parts of this form of pyrometer consist of a metal cylinder or bulb containing the working substance, connected by

metal tubing to a Bourdon gauge calibrated to read temperatures directly. The bulb of the pyrometer can be inserted in the steam pipe, exhaust pipe or flue of a boiler, and the vapour pressure set up within the instrument by the rise in temperature operates the gauge, and the temperature can be read. Water instruments have a range from 212° F. to 700° F., while mercury instruments can record temperatures up to 1400° F.

Electrical instruments depending upon the alteration of resistance with rise of temperature are also widely used for recording high temperatures. These instruments provide a most reliable and accurate way for direct reading in Fahrenheit or Centigrade, or for a continuous permanent record which can be made on a paper-covered drum.

Thermo-electric pyrometers employ the principle that when two pieces of dissimilar metals are joined at their ends and the joints kept at different temperatures a difference of potential is produced between the junctions, and an electric current will pass. The magnitude of the current depends upon the difference of temperature existing between the junctions, and can be easily measured.

High temperatures can also be measured by the change of colour of a heated body from red to white with rise of temperature, and by the great increase of brilliancy which is known to accompany the change. Instruments employing this principle are called **optical** or **photometric pyrometers**, as they possess means of measuring the intensity of light emitted. Men long accustomed to furnace control work can estimate furnace temperatures, merely by sight, to a surprising degree of accuracy.

The experiment which follows illustrates a very approximate method of determining high temperatures by the method of mixtures. If the mean specific heat of the metal over the range of temperature involved is accurately known, there is some justification for the employment of the method, and it serves in a general way to determine an approximate value for the temperature.

Expt. 24.

Object. *To find the mean temperature of the exhaust gases of an internal combustion engine employing the method of mixtures.*

APPARATUS. A block of copper, calorimeter, thermometer, balance and weights.

METHOD OF PROCEDURE. Some difficulty is experienced in determining the temperature of the exhaust in an internal combustion engine, or the temperature of a furnace, without the use of an expensive pyrometer. The method of the experiment will give an approximate temperature under mean conditions. Insert the copper block in the exhaust and allow it to remain long enough for its temperature to become equal to that of the exhaust. Remove the block and quickly transfer to a calorimeter of water of known weight and temperature, stir and note the temperature of the water. Then if the weight of the copper block is known and the specific heat of copper is either known or is determined, the heat lost by the copper will be equal to the heat gained by the calorimeter and the water. Thus the temperature of the copper before transfer to the water, that is, the temperature of the exhaust, can be deduced.

OBSERVATIONS.

Weight of copper block	= 0·25 lb.
Weight of calorimeter	= 0·15 lb.
Weight of water	= 0·8 lb.
Specific heat of copper	= 0·09.
Initial temperature of water	= 60° F.
Final temperature of water	= 73° F.
Rise of temperature	= 13° F.

DERIVED RESULTS.

Heat given to calorimeter and water is equal to the heat lost by the copper.

Water equivalent of calorimeter = $0·15 \times 0·09 = 0·0135$ lb.
Total equivalent weight of water = $0·0135 + 0·8 = 0·8135$ lb.
Heat given to water = $0·8135 \times 13$ B.Th.U.
Let T be the temperature of exhaust in ° F.
Heat lost by copper = $0·09 \times 0·25 \times (T - 73)$ B.Th.U.

$$0·8135 \times 13 = 0·09 \times 0·25(T - 73),$$

or heat gained by water and calorimeter = heat lost by copper ;

$$10·5755 = 0·0225T - 1·6425,$$

$$0·0225T = 12·218,$$

$$\therefore T = 543° \text{ F}.$$

Temperature of exhaust = 543° F.

Properties of Saturated Steam.*

Absolute pressure, lb in.²	Temp., °F.	Volume of 1 lb of dry steam in cu ft.	Total heat of liquid, B.Th U	Latent heat, B Th.U.	Total heat of dry steam B Th.U.	Total heat of liquid, C H.U.	Total heat of steam, C.H.U.	Temp., °C.
0·5	79·5	640·5	47·4	1044·7	1092·1	26·33	606·73	26·40
1	101·7	333·1	69·5	1032·9	1102·4	38·62	612·46	38·73
3	141·5	118·6	109·3	1011·3	1120·6	60·70	622·53	60·83
4	153	90·54	120·8	1004·9	1125·7	67·10	625·38	67·23
4·4	156·9	82·8	124·7	1002·7	1127·4	69·28	626·34	69·40
4·6	158·8	79·42	126·6	1001·6	1128·2	70·31	626·79	70·43
4·8	160·6	76·31	128·3	1000·7	1129·0	71·30	627·22	71·42
14·689	212	26·79	180	970·7	1150·7	100·00	639·30	100·00
20	228	20·08	196·1	961	1157·1	108·95	642·82	108·87
22	233·1	18·37	201·3	957·8	1159·1	111·83	643·92	111·71
30	250·3	13·72	218·8	946·7	1165·5	121·5	647·5	121·3
50	280·9	8·5	250	926·3	1176·3	138·9	653·5	138·3
80	311·9	5·466	281·9	904·2	1186·1	156·6	658·9	155·5
120	341·3	3·727	312·5	881·8	1194·3	173·6	663·5	171·8
150	358·4	3·016	330·6	867·9	1198·5	183·7	665·8	181·3
180	373·1	2·536	346·1	855·6	1201·7	192·3	667·6	189·5
200	381·8	2·293	355·5	848	1203·5	197·5	668·6	194·3
215	~~387·9~~	2·140	362·1	842·7	1204·8	201·1	669·3	197·7
220	389·9	2·093	364·2	840·9	1205·1	202·3	669·5	198·8
240	397·4	1·926	372·4	834	1206·4	206·9	670·2	203·0
260	404·5	1·783	380·1	827·4	1207·5	211·1	670·8	206·9
270	407·9	1·719	383·7	824·3	1208	213·1	671·1	208·8
300	417·4	1·552	394·2	815·2	1209·4	219·0	671·9	214·1
310	420·4	1·504	397·5	812·3	1209·8	220·8	672·1	215·8
320	423·4	1·458	400·8	809·4	1210·2	222·6	672·3	217·4
330	426·3	1·415	404·0	806·5	1210·5	224·4	672·5	219·0
340	429·1	1·374	407·1	803·7	1210·8	226·1	672·7	220·6
400	444·7	1·172	424·6	787·5	1212·1	235·9	673·4	229·3
410	447·2	1·144	427·3	785	1212·3	237·4	673·5	230·6
420	449·5	1·118	430	782·4	1212·4	238·9	673·6	231·9
480	462·9	0·979	445·3	767·8	1213·1	247·4	673·9	239·4
500	467·1	0·940	450·1	763·1	1213·2	250·0	674·0	241·7
1000	544·7	0·458	544·1	660·2	1204·3	302·8	669·1	287·1

* Extracted with permission from "Abridged Callendar Steam Tables" published by Messrs. Edward Arnold & Co.

EXERCISES ON CHAPTER II

The heat engine and the properties of working substances. Gas laws.

1. What is the function of a heat engine?

Explain briefly why gases and vapours form better working substances for heat engines than liquids and solids.

2. State Boyle's law, and describe how you would verify it by experiment.

3. 6 cu. ft. of air are compressed very slowly from 14·5 lb. per sq. in. absolute to 100 lb. per sq. in. absolute. What is the final volume of the air?

4. Steam is admitted to the cylinder of a locomotive and has a pressure of 180 lb. per sq. in. absolute. If the steam supply is cut off when the volume is one-fifth of its final volume, calculate the final pressure, assuming hyperbolic expansion or expansion according to Boyle's law.

5. The delivery valve of a gas reservoir of capacity 1000 cu. ft. opens when the internal pressure is 100 lb. per sq. in. abs. What volume of gas must be pumped in at N.T.P. to fill the reservoir completely? Assume the temperature remains constant.

6. $\frac{1}{3}$ of a cubic foot of steam at 220 lb. per sq. in. expands isothermally to a volume of $\frac{2}{3}$ of a cubic foot. What is its final pressure? What law is involved in obtaining the solution to this question?

7. What volume of compressed air at 2500 lb. per sq. in. (gauge) must be used to blow sea water from a ballast tank of a submarine if the latter is at a depth of 180 ft. Capacity of tank, 600 cu. ft. Assume there is no change of temperature. Sea water weighs 64 lb. per cu. ft.

8. State Charles' laws, and describe an experiment to verify one of them.

9. What do you understand by the terms *absolute pressure* and *absolute temperature?* Express a gauge pressure of 63 lb. per sq. in. as an absolute pressure and temperatures of 38° C. and 230° F. as absolute temperatures.

10. If the pressure on a gas remains constant and its initial volume and temperature are 40 cu. ft. and 15° C. respectively, what will its final temperature be if the volume has increased to 60 cu. ft., and its final volume if the temperature has increased to 303° C.?

11. A quantity of acetylene gas in a cylinder has an absolute pressure of 20 atmospheres and a temperature of 15° C. If the temperature were accidentally raised to 591° C., estimate the gas pressure reached in lb. per sq. in. Ignore the expansion of the cylinder.

12. 40 cu. ft. of hydrogen at 400° C. is reduced in volume at constant atmospheric pressure so as to occupy 18 cu. ft. Find the final temperature.

13. Find the initial temperature of some gas which is heated at constant pressure to 627° C. to three times its original volume.

14. Explain the combined law which connects, for the different states of any given mass of gas, the absolute pressure, volume and absolute temperature.

A given mass of gas occupies 10 cu. ft. at 0° C. and 1 lb. per sq. in. gauge. What volume would it have if the temperature were raised to 50° C. and its pressure to 171 lb. per sq. in. gauge?

15. The gases in the cylinder of an engine expand to six times their original volume. If the initial pressure is 450 lb. per sq. in. and the final 20 lb. per sq. in. and the exhaust temperature 800° F., what is the initial temperature?

16. Forty cubic feet of air at atmospheric pressure (14·7 lb. per sq. in.) and at a temperature of 10° C. are compressed into a vessel having a capacity of 8·7 cu. ft., and the temperature immediately after compression is 105° C. Determine the resulting pressure, and also the pressure drop when the temperature has fallen to its original temperature of 10° C. (U.L.C.I.)

17. What is meant by *normal temperature and pressure*? At 60° F. and pressure $\frac{1}{4}$ lb. per sq. in. gauge a quantity of coal gas occupies 10 cu. ft. What volume does it occupy at N.T.P.?

18. Oxygen at a pressure of 15 lb. per sq. in. abs. and temperature 14° C. is compressed into a cylinder of 1 cu. ft. capacity to a pressure of 400 lb. per sq. in. abs. After compression the temperature of the gas rose to 75° C. Find the volume of the oxygen in its original state. Also find the final pressure and the weight of oxygen in the cylinder after it has cooled to 15° C. R for oxygen = 89·6 ft. lb. per lb. per Cen. degree.

19. An engine consumes 3·6 cu. ft. of gas per min. measured at a temperature of 17° C. and gauge pressure of 5 in. of water and barometer reading of 29·8 in. Find the calorific value of the gas per cu. ft. as used if, at N.T.P., its calorific value is 490 B.Th.U. per cu. ft.

20. The characteristic constant R for ethylene is 64·6 ft. lb. per lb. per Fahr. degree. Calculate the specific volume of ethylene, (a) at N.T.P., and (b) at 100 lb. per sq. in. abs. and 120° F.

21. The capacity of an air compressor is 1800 cu. ft. per min. at 60° F. and 14·7 lb. per sq. in. abs. Find the weight of air dealt with per minute. $R = 53{\cdot}2$ ft. lb. per lb. per Fahr. degree.

22. What is the *characteristic equation of a gas?*

6 cu. ft. of methane at N.T.P. is compressed to occupy $1\frac{1}{2}$ cu. ft. at a pressure of 80 lb. per sq. in. gauge. Calculate the final temperature of the methane.

23. Find the weight of the gas mentioned in Question 22 if c_p for methane $= 0{\cdot}591$ and $\gamma = c_p/c_v = 1{\cdot}313$.

24. *In a gas engine the temperature and pressure of the charge at* the end of compression are 180° C. and 60 lb. per sq. in. abs. respectively. Heat is then supplied at constant volume by allowing the charge to explode instantaneously when the pressure reaches 310 lb. per sq. in. abs. What is the final temperature?

25. What is the amount of heat taken in by the charge per lb. at constant volume in Question 24 if c_v is 0·17?

26. What is the characteristic constant for a gas and in what units is it usually expressed?

Find the characteristic constant for carbon monoxide if 2 cu. ft. at 14° C. and 300 lb. per sq. in. abs. weighs 3·107 lb.

27. c_p for chlorine is 0·116 and $\gamma = c_p/c_v = 1{\cdot}34$, calculate the value of the characteristic constant R. Find the weight of 10 cu. ft. of chlorine if its temperature is 16° C. and pressure 300 lb. per sq. in. abs.

28. At the end of its stroke a piston working in a cylinder has compressed some air into a space of volume 250 cu. in. Fuel is then injected into this compressed air and fired, and the piston is pushed forward a distance of 20 in. What is the compression ratio of this engine? Dia. of cylinder = 15 in.

29. If a quantity of gas expands according to the law $PV^n = K$, sketch a few expansion curves to illustrate how P varies with V for a few values of n. Find the amount of work done when $n = 0$, the effective pressure 100 lb. per sq. in., and the volume changes from 1 cu. ft. to 6 cu. ft.

30. If the mean effective pressure acting on the piston of an engine is 90 lb. per sq. in., while the volume of the expanding gas changes from $1\frac{1}{2}$ cu. ft. to 7 cu. ft., calculate the work done.

31. Explain briefly what adiabatic expansion means, and how it differs from isothermal expansion. In which type of expansion is more work done?

32. If 4 cu. ft. of gas at 200 lb. per sq. in. abs. expands according to the law $PV^{1{\cdot}2} = K$, determine the final pressure when the volume has become 10 cu. ft. What would the final pressure have been if the expansion had been isothermal?

33. If a compressor changes the state of 2000 cu. ft. of air per min. from 15° C. and 14·7 lb. per sq. in. abs. to a pressure of 120 lb. per sq. in. abs. according to the law $PV^{1{\cdot}3} = K$, what is the final volume? What would the final volumes be for adiabatic and isothermal compression? $\gamma = 1{\cdot}4$. What is the ratio of compression?

34. 2 cu. ft. of ammonia is compressed adiabatically from a pressure of 15 lb. per sq. in. abs. to a pressure of 400 lb. per sq. in. What is its final volume? If the final volume had been 10 cu. ft., what would the final pressure have been? γ for ammonia = 1·336.

35. $1\frac{1}{2}$ cu. ft. of gas at 300 lb. per sq. in. abs. at 1300° F. expands until it has a volume of 6 cu. ft. according to the law $PV^{1\cdot3}=K$. Find the final pressure and temperature of the gas.

36. Calculate the final volume and temperature and the ratio of expansion when $2\frac{1}{2}$ cu. ft. of gas initially at 320 lb. per sq. in. abs. and 900° C. expands until its final pressure is 45 lb. per sq. in. abs. according to the law $PV^{1\cdot35}=K$.

37. In Question 36, if the expansion had been adiabatic, calculate the final volume and temperature. $\gamma=1\cdot4$.

38. Enumerate the chief properties of gases, including the quantitative types of properties, which the engineer employs.

Steam quantities.

39. Using water-steam tables, find the saturation Centigrade temperatures corresponding to pressures of 395·3 lb. per sq. in. gauge and 180 lb. per sq. in. absolute.

40. What are the saturation steam pressures corresponding to boiling points at 67·23° C., 197·7° C., and 287·1° C.?

41. Feed water at 100° F. is supplied to a boiler of working pressure 240 lb. per sq. in. abs. Find the amounts of sensible and latent heats to be supplied per lb. of dry steam generated.

42. Describe an experiment to show how the pressure on the surface of water affects its boiling point.

43. The total heat of dry saturated steam per lb. at 600 lb. per sq. in. abs. is 673·8 C.H.U., while the sensible or liquid heat is 262·5 C.H.U. What is the latent heat in C.H.U. and B.Th.U. per lb. at this pressure? Also what is the total heat of wet steam at this pressure if the dryness fraction is 0·95?

44. Assuming hyperbolic expansion and a ratio of expansion of 6, draw the expansion curve of 1 lb. of wet steam initially at 220 lb. per sq. in. abs. and 95·6% dry. What is the final volume?

45. By means of a multiple axes graph determine from the following tabulated values (*a*) the saturation temperature, (*b*) the specific volume, and (*c*) the total heat of dry steam at 316 lb. per sq. in. abs.

Pressure lb. per sq. in. abs.	290	300	310	320	330	340
Saturation temperature ° F.	414·3	417·4	420·4	423·4	426·3	429·1
Specific volume in cu. ft. per lb.	1·604	1·552	1·504	1·458	1·415	1·374
Total heat B.Th.U./lb.	1209·0	1209·4	1209·8	1210·2	1210·5	1210·8

46. Find the total heat of dry saturated steam at 300 lb. per sq. in. (absolute) in B.Th.U. and C.H.U.

47. The data given below are taken from a steam table. Complete the table, and then calculate the amount of heat required to convert completely 20 lb. of water at 52·27° C. to dry saturated steam at a pressure of 150 lb. per sq. in. absolute.

Pressure (lb per sq. in.)	Temp.	Total heat of liquid (C.H.U.)	Latent heat (C.H.U.)	Total heat of steam (C.H.U.)
2	52·27	—	566·51	618·67
150	181·31	183·59	—	666·49
250	205·1	209·07	463·01	—

(U.L.C.I.)

48. Explain the meaning of "sensible" and "total" heat of dry saturated steam.

Determine the number of heat units required to generate 3000 lb. of dry saturated steam at an absolute pressure of 200 lb. per sq. in. from water at 80° C.

Temp. of steam at 200 lb. per sq. in. is 194·4° C. Sensible heat 197·5 C.H.U. per lb. Total heat 669·7 C.H.U. per lb. (U.L.C.I.)

49. Sketch in outline and describe how you would use the apparatus for the determination of the temperature of saturated steam at various pressures. (U.L.C.I.)

50. Steam is supplied to a turbine at 400 lb. per sq. in. (abs.) and superheated to 725° F. What is its total heat per lb. ? After passing through several stages the pressure drops to 35 lb. per sq. in. (abs.). Assuming the steam is still dry, calculate the heat drop per lb. Use tables, and take the specific heat of the superheated steam as 0·6.

51. The boiler of an electricity works evaporates 7·81 lb. of water for every lb. of fuel fired. The water is raised in temperature from 80° C. to 414° C. at a pressure of 300 lb. per sq. in. abs. Calculate (using tables) the heat imparted to the steam per lb. of fuel. If the calorific value of the coal is 6365 C.H.U., what is the efficiency of the transfer of energy ? $c_p = 0·563$.

52. A Thornycroft boiler generated 13 lb. of dry saturated steam at 240 lb. per sq. in. (abs.) per lb. of oil fuel from feed water at 46° F. What is the heat gained by the water per lb. of fuel in B.Th.U. and also in C.H.U. ?

53. What do you understand by the "dryness fraction" of wet steam ? How much steam, at 200 lb. per sq. in. (gauge) and dryness fraction 0·8, must be blown into ½ ton of water at 0° C. to raise its temperature to boiling point ?

54. Compare the performances of two boilers, one of which raises 13¾ lb. of water from feed temperature of 70° F. to dry saturated steam at 200 lb. per sq. in., while the other raises 11½ lb. of water from 45° F. to dry saturated steam at 250 lb. per sq. in. The weights of water are per lb. of oil fuel in each case, and the pressures are absolute pressures.

55. 8700 lb. of steam per hour at 22 lb. per sq. in. (absolute) and dryness fraction 0·9 is tapped off, or bled, from a turbine to heat boiler feed water. What weight of feed water could be raised from 100° F. to 200° F.?

56. Find the increase in specific volume from wet steam of dryness fraction 0·96 at 400 lb. per sq. in. abs. to steam at the same pressure with 400° F. of superheat. Use $V = 1{\cdot}2464(H - 835)/P$.

57. Superheated steam at 1000 lb. per sq. in. abs. and 400° of superheat has a total heat of 1475·5 B.Th.U. per lb., while its total heat of saturation at this pressure is 1204·3 B.Th.U. per lb. Calculate the mean value of c_p for superheated steam for this pressure for the range of superheat specified.

58. Using the following values taken from Callendar's Abridged Steam Tables, plot a graph and determine from it the total heat of superheated steam at 500 lb. per sq. in. abs. with 108° of superheat.

Degrees Centigrade of superheat	80	90	100	120	140
Total heat in C.H.U. per lb. at 500 lb. per sq. in. abs.	727·3	733·3	739·2	750·5	761·7

59. 10 lb. of steam blown into 300 lb. of water raises the temperature of the latter from 10° C. up to 30° C. If the steam pressure was 240 lb. per sq. in. abs. estimate its dryness fraction.

60. Describe an experiment for determining the dryness fraction of steam, either (*a*) by means of a separating calorimeter, or (*b*) by means of a throttling calorimeter.

61. Sketch and describe apparatus for determining the properties of superheated steam, and explain how it is used.

62. Describe briefly some of the means adopted for measuring high temperatures, and indicate in each case the physical principles employed.

CHAPTER III

TRANSMISSION OF HEAT TO THE WORKING SUBSTANCE IN EXTERNAL COMBUSTION ENGINES—THE STEAM POWER PLANT—AUXILIARIES

HEAT engines can be roughly divided into two types, namely, (1) the external combustion engine and (2) the internal combustion engine.

In an external combustion engine the fuel is burnt in a separate vessel, where the heat generated by the burning fuel is imparted to the working substance. This working substance is then allowed to expand in the engine and do work. The chief example of this type is the steam engine. Steam is generated in a vessel called a boiler, and then it passes to the steam engine or turbine and by the force of its expansion does external mechanical work on the piston or turbine rotor. In the internal combustion engine the fuel and air mixture is burnt in the engine cylinder, the rise of temperature and pressure produced in the working substance enabling it to do work in expansion (see Chap. V).

The steam engine plant (open-feed system). Fig. 36 shows in outline the essentials of a simple steam engine and the various apparatus necessary for functioning it. It must be remembered that there are many arrangements or types of plant, although the principles involved are mainly the same and all employ steam as the working substance. The principal parts of the plant are (1) the boiler, (2) the engine, and (3) the condenser. The latter is not an absolute necessity, and is often omitted on the score of simplicity and the saving of space, as in the case of the steam locomotive. In fact, steam engines can be classified under the two heads, (*a*) condensing engines or (*b*) non-condensing engines, although some engines are constructed to function with or without a condenser.

(1) The boiler. This occupies the major portion of the whole space taken by the plant, and it must be very carefully constructed and

needs expert care in working and maintenance. In the type of boiler outlined in the diagram, steam is generated by employing an oil-fired furnace. Oil is drawn from tanks through pipes and coarse strainers by pumps delivering it through filters and heaters to the burners on the boiler front. The oil is then sprayed into the furnace, producing, with the air supplied, smokeless combustion and an equal distribution of heat. It may also be mentioned that the oil-fired boiler has a high efficiency as none of the parts gets sooty, the

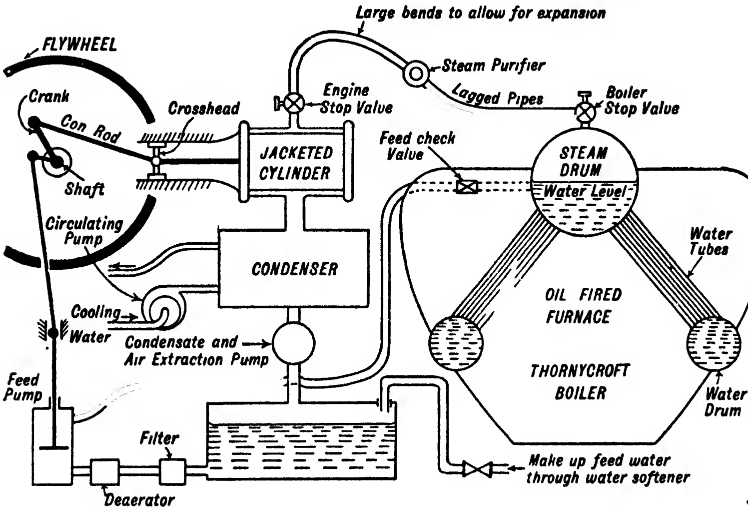


FIG. 36. Simple steam power plant. (Open-feed system.)

boilers are smaller for equal power than with coal-fired boilers, and there is a more ready control of combustion and hence in the amount of steam produced.

Every effort is made to design the boiler so that the heat of combustion reaches the water through the tubes and water drums. In the modern boiler the water is quickly and economically converted into steam, whence it passes to the engine cylinder through a pipe, which is covered with non-conducting material, known as lagging, to prevent the steam becoming cooled and partially condensed. This pipe, being subjected to a large range of temperature and connecting two fixed bodies, namely, the engine and the boiler, has

bends of large radius which readily allow for expansion and prevent straining of the joints and consequent leakage. Steam supply from the boiler is controlled by the **boiler stop valve,** while before the steam reaches the engine stop valve it is usually passed through a steam separator or purifier to rid it of water particles and any solid or liquid impurities. Later it will be seen that dry steam is necessary for the efficient working of a steam engine.

(2) **The engine cylinder.** The entry of steam into the cylinder is controlled by means of valves, while some of the boiler steam is used to form a hot jacket around the outside of the cylinder liner in order to prevent excessive condensation of steam as it cools during expansion. To convert the straight line, to and fro, or reciprocating motion of the **piston,** which is forced along by the expanding steam, into rotating motion, a **crosshead, connecting rod,** and **crank** are employed. It is the crank which rotates the shaft and flywheel, and the kinetic energy given to them is utilised in doing mechanical work. The expanded steam after it has done its work may be exhausted directly to the atmosphere, or condensed in a condenser.

(3) **The condenser.** In order that the steam can be expanded to its full limit and to enable the fresh water to be used again, which is important in ships, the steam is often condensed in a condenser in which a partial vacuum is formed, thus reducing the back pressure on the piston. By condensing the steam, say at 1 lb. per sq. in. absolute, to water, its volume is reduced in the ratio of about 20,800 : 1. If this is done in a closed vessel, it follows that an empty space, void, or vacuum tends to be formed. It is possible to increase the partial vacuum or maintain the vacuum by removing any air which has leaked into the condenser by means of an **air pump.** Thus if the reverse side of the piston to that upon which the boiler steam is acting is connected to the condenser, there will be less resistance, or less back pressure offered, and expansion can be economically carried to a further stage. In non-condensing engines the back pressure is that due to the atmosphere (see p. 30).

The steam is condensed by the action of cooling water, which, in the surface type of condenser, is made to circulate through tubes by means of a pump known as a **circulating pump.** Meanwhile the

latent heat of the steam is extracted by coming into contact with the outside of the comparatively cold tubes. Air, which has entered with the steam or leaked into the condenser, and the condensed water are withdrawn by a pump and discharged into a tank that acts as a feed tank to supply more water for the boiler, unless as in experimental engines it is desired to measure the condensate. This pump is often called an air pump, because it abstracts air as well as condensate, and prevents the vacuum from being reduced or destroyed by leakage. The **feed pump** draws water from the **feed tank,** often called the **hot well,** and forces it into the boiler. Sometimes the water is passed through filters, oil extraction apparatus and deaerators to extract sediment, oil and air respectively before they can reach the feed pump. The substances mentioned are detrimental to the functioning and long life of the boiler. Occasionally the feed pump is driven by an electric motor, but it will be noticed that the feed pump is shown in the diagram as being operated by the engine crank shaft. **A feed check valve** serves to control the entry of feed water into the boiler.

To replace the leakage of steam and water from the system, what is called 'make up feed water' must be supplied from some source, and this fresh water may with advantage be passed through a **water softener,** which removes most of the dissolved solids and so prevents them from being deposited in the boiler. More details of the various parts mentioned will be given later in this chapter.

The simple type of steam plant just described provides an example of the open-feed system, so called because the feed water comes into contact with the atmosphere.

Layout of a steam power plant (closed-feed system). Fig. 37 is an outline of the layout of a steam power plant, which is a heat engine plant using water vapour, or steam, as the working substance to convert the heat energy liberated by the combustion of the fuel into mechanical work. The main components are (1) the steam generator or boiler, (2) the engine in which the steam expands and does mechanical work, and (3) the condenser in which the steam is condensed ready for pumping back into the boiler. To improve the efficiency of the plant as a whole, various auxiliary apparatus

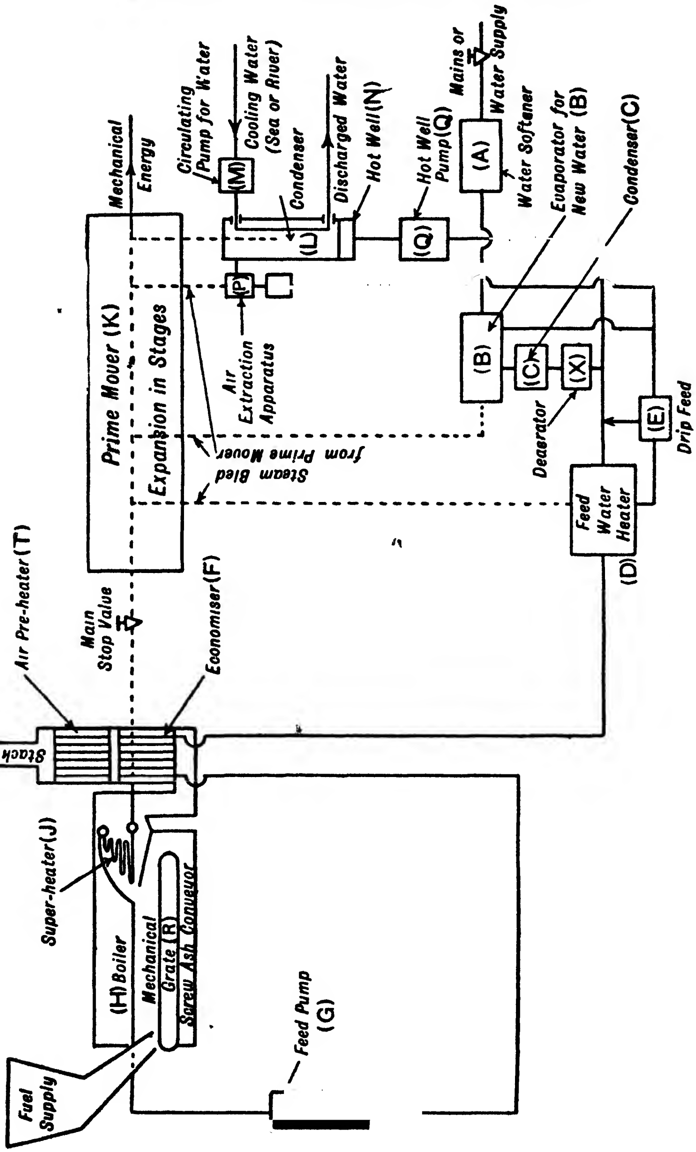


FIG. 37. Layout of a steam power plant.

and accessories are added. It must be remembered that the plant *contains a large quantity of working fluid continually being circulated and that a small leakage has to be made good from the* supply.

Suppose the path followed by the water in the plant is taken up where fresh water is being supplied to provide for this leakage. From the mains, or source of supply, the water can advantageously be passed through a **water softener**, A, to prevent the deposition of fur or boiler crust in the system. Water hardness is due to the solids generally found dissolved in water, and if these can be precipitated and filtered off, waste of fuel and damage to boiler parts can be lessened. Water which is unduly soft is also injurious to the boiler structure, and it is in rare cases necessary to slightly harden the water before use. From A the water passes to the **evaporator**, B, where it is converted into steam, the necessary heat being obtained from steam abstracted, or bled, as it is called, from a suitable point in the expansion in the engine, or **prime mover.** The solid matter in the mains water is left in the evaporator, where it does little harm and can easily be removed, while the water itself has been converted to steam and flows into a **condenser**, C. Here it is condensed, but before being allowed to enter the main stream of feed water it is passed through a **deaerator**, X, to remove dissolved gases. The whole stream of feed water now enters one or more **feed water heaters**, D, in which the boiler feed water is heated by steam bled from a suitable point, or points, in the steam expansion in the prime mover. Bled steam that has been condensed in heating feed or make up feed water is pumped back into the main system by the **drip feed pump**, E. From the heaters, D, the feed water passes through the tubes of the **economiser**, F, situated in the boiler flue, where it is still further heated by the furnace gases before being forced into the **boiler**, H, by the **feed pump**, G.

In the boiler the water is converted into steam, where it passes through the **superheater**, J; here its total heat is increased at constant pressure ready for economical expansion in the engine itself. The latter may be a **steam turbine**, K, or perhaps a **triple or quadruple expansion engine.** In both cases the expansion of the steam is carried out in stages, to prevent or lessen condensation, before it is ex-

hausted into the surface **condenser,** L. To condense the steam, cooling water is made to flow continuously through the condenser by means of the **circulating pump,** M, but is not allowed to mix with the steam in process of condensation. The condensed steam, or condensate as it is often called, drops into the **hot well,** N, which acts as a feed tank. Small quantities of air which have leaked into the condenser, and which if allowed to remain in the system would increase the back pressure on the prime mover and prevent expansion reaching such an advanced stage, are removed by the **air ejector,** P, which requires steam to operate it. The **hot well pump,** Q, draws water from the condenser and forces it back over the path it has already traversed, any loss of working fluid being made good by the small distilling plant B and C already mentioned. Between the hot well pump, or 'condensate extraction pump' as it is sometimes referred to, and the boiler feed pump it is generally necessary to provide a **surge tank** in which feed water can be stored. In this way variations in the supply and demand of feed water can be met, irrespective of the amount of condensate available. It should be noticed that in this water-steam circulation the highest pressure exists between the boiler feed pump and the prime mover, while the lowest pressure exists between the prime mover and the hot well pump.

The fuel is usually supplied through a hopper to a slowly moving **mechanical grate,** R, upon which combustion is controlled. Where oil fuel or pulverised fuel is used, special plant, burners and combustion chambers must be installed. The heat liberated by combustion raises the temperature of the water in the boiler tubes and drums and generates the steam. Then the hot gaseous products of combustion pass on to heat the superheater tubes and to the flues through the economiser and **air preheater,** T. The air supply to the furnace passes through T, and is thus heated above atmospheric temperature. Often the ash is removed from the end and beneath the mechanical grate by means of a screw ash conveyor, or some similar contrivance.

The more important of the various parts mentioned will now be dealt with in more detail.

Water softener. One type of softener is the Kennicott water softener. This employs a mineral called Kenzelite, which has the

property of combining with all the lime and magnesia contained in the water passing through it. When exhausted the mineral can be regenerated, or revived, by passing brine through it, and is thus practically everlasting. This plant automatically softens the water, no matter how the hardness may vary, and is entirely satisfactory where the make up feed water does not exceed 5% of the total. It is most important that the dissolved solids should not reach the boiler and economiser tubes to be deposited as a hard crust, restricting the flow of water and making the transfer of heat through the tubes much more difficult. A water softener is an absolute necessity in the case where the water is not distilled. A crust on an economiser or boiler tube is a bad conductor of heat, and thus the heat from the flue gases is unable to pass freely to the water in process of evaporation.

Deaerator. This is an increasingly popular addition to the auxiliary plant. Experience led to the discovery that if the dissolved oxygen in the feed water is kept below $\frac{1}{10}$ c.c. per litre, the corrosion in boilers, economisers and turbines is almost entirely prevented. More recent experience shows that the water can be saturated with oxygen, but there is no corrosive action on steel, providing there is no trace of carbon dioxide present. Even in a closed feed system, air tends to leak in and mix with the condensate, so this air must be removed. In a type of deacrator made by Messrs. Hick, Hargreaves & Co., the feed water (if under 130° F.) is heated by steam and then suddenly injected through an atomising spray nozzle valve into a low pressure chamber, thus quickly reducing the temperature and pressure of the water and causing it to boil violently and liberate the dissolved gases. The latter are removed by an air ejector pump which so maintains the vacuum, while an extraction pump withdraws the water. A bucket float controls the flow of water to the nozzle valve. A deaerator may be regarded as an absolute necessity in the case of the **open feed system,** where the boiler feed comes into contact with the atmosphere. In the closed system the make up feed, to allow for leakage and loss through safety valves, is usually passed through a deaerator.

Bled steam is steam taken from the engine at some stage of the expansion and used to function the auxiliary boiler plant.

Feed heaters. These utilise exhaust or *bled* steam to heat the feed water before it enters the economiser or boiler. The water is made to pass through tubes in the opposite direction to the normal flow of steam on the outside, thus making use of the **contra-flow principle.** The tubes may be made of solid drawn copper or brass, or for higher temperatures of steel or cupro-nickel. Cast iron or steel are generally used for the covers, water boxes and body, while provision must be made for the expansion of the tubes in fastening them to the body. The bled steam is taken at a convenient point in the expansion stages in the prime mover, and there may be as many as five feed heaters, each taking its supply of steam from different points and each raising the temperature of the feed water 40-50 Fahr. degrees.

In the closed feed system to the boiler, now being described, care is taken that only distilled and deaerated water enters the circulation, but in less efficient types of steam plant the feed heaters serve the useful purpose of driving off dissolved air and allow dissolved solids to be deposited where they can be easily removed. After it has done useful work in the prime mover, the extracted steam gives up the whole of its latent heat to the feed water, which means less heat is rejected to the condenser, and there is a consequent saving of fuel. As less work remains to be done in the boiler itself the evaporative power is increased, and there is less strain on the boiler because of the smaller range of temperature involved. The design of feed heaters must be such that arrangements can be made for periodical cleaning, for removal of feed water scale inside the tubes, and oil and grease from the exhaust steam of reciprocating engines on the outside.

Feed pump. This is often worked directly from the prime mover, but sometimes by a separate engine or motor. It must be able to pump from 2 to $2\frac{1}{2}$ times the amount of theoretical feed required by the boiler after allowance has been made for leakage, and must be capable of forcing this water into the boiler. In modern practice the feed pump is generally of the centrifugal type driven by an electric motor or steam turbine. For small plants the pump may be of the reciprocating type, and would probably be driven from the engine shaft by an eccentric attached to the pump plunger.

When worked independently of the engine the pump is often called a donkey pump.

Boilers, or steam generators. There are many kinds of boilers and they may be classified under two headings, namely:

(1) **fire tube boilers,** in which the products of combustion pass through tubes surrounded by water on the outside;

(2) **water tube boilers,** in which the water flows through the tubes and the hot gases flow over the outside.

The Cornish, Lancashire, locomotive and the older marine type of boiler are fire tube. The Babcock and Wilcox, Stirling, Thornycroft and Yarrow boilers are examples of the water tube type.

Transmission of heat in a boiler. If a poker be placed in the fire, heat flows along it, even though its cooler end be screened, and the poker is said to be heated by **conduction.** In the same way the furnace tubes receive some of their heat by conduction from the hot furnace bars because iron is a good conductor of heat. This heat seems to flow from particle to particle of the iron, the temperature of each particle gradually rising. When a person is seated before a fire, or in the sun, he absorbs heat, and the heat is said to be transmitted by **radiation** because the intervening air is not heated as in conduction. Dull black surfaces are the best absorbers of radiant heat. In the same way the furnace tubes receive the heat radiated from the furnace and hot products of combustion. The water in contact with the hot furnace tubes receives heat, expands, becoming less dense than the water around it. It rises and is replaced by colder and denser water, which is in its turn heated, thus setting up currents flowing in the water in the boiler. The process of heating fluids by movement of the particles of the water themselves is termed **convection.**

Heat can thus be transmitted in three ways. Water and air are poor conductors of heat, and they are best heated by convection. Metals are good conductors and absorb radiant heat, unless they are highly polished, when the heat is reflected.

The following experiments illustrate the three modes of transferring heat, a knowledge of which is of prime importance to the engineer.

EXPT. 25. **Transfer of heat by conduction.**

OBJECT. *To compare the conductivities of copper, iron and brass rods.*

APPARATUS. Three rods of copper, iron and brass (Fig. 38), each about $\frac{3}{16}$ in. dia., 15 in. in length, and a block of iron or copper about 1 in. square section and 6 in. in length.

METHOD OF PROCEDURE. Heat the block of iron uniformly in a tinmen's stove or small furnace until it is uniformly heated. Coat the three rods with a thin coat of molten paraffin wax, and after removing the block from the fire arrange the rods as shown in Fig. 38 with their ends in contact with the hot block. The wax will melt off the rods for varying lengths, and after a time no further melting will occur. This takes place when the rate of conduction of heat along the rod is the same as the loss of heat from the surface

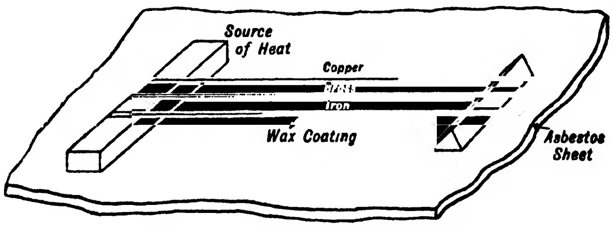


FIG. 38. Relative conductivity.

into the atmosphere. Measure the distances uncovered for each rod, and thus obtain the relative conductivities of the materials from which they are made.

It will be seen that copper is a good conductor of heat and is said to have a high thermal conductivity. Compared with other substances most metals are good conductors.

The conditions which facilitate a transfer of heat by conduction are a close contact between the particles and a temperature difference existing between them. The more intimate the contact and the greater the difference of temperature, the more rapid the flow of heat from the hotter to the colder particles by conduction, tending to equalise the temperature. In the boiler plant the scouring or scrubbing action of the hot turbulent gases against the cooler boiler or economiser tubes helps the transfer of heat from gas to metal by conduction. A similar action occurs between the steam and the cooling water tubes in a surface condenser.

When it is necessary to conserve the heat in boilers, engine cylinders and steam pipes, the engineer encases or lags them with

substances which are poor conductors of heat. The following experiment will illustrate how differing substances may be compared for this purpose.

EXPT. 26.

OBJECTS. (1) *To test the relative lagging qualities of magnesia section covering and plastic compound supercoated with asbestos composition.*

(2) *To find the weight of steam condensed in a given period in pipes (a) bare, (b) lagged with varying materials.*

APPARATUS. Three similar service steam pipes (Fig. 39) about 3 inches diameter, served from the normal steam supply at a known pressure. One of these pipes is left bare and the other two lagged with (*a*) magnesia section covering, (*b*) a plastic compound supercoated with asbestos composition. The pipes are set vertically and the tops and bottoms fitted with suitable flanges. Inlet of steam is arranged at the top and drain cocks at the bottom.

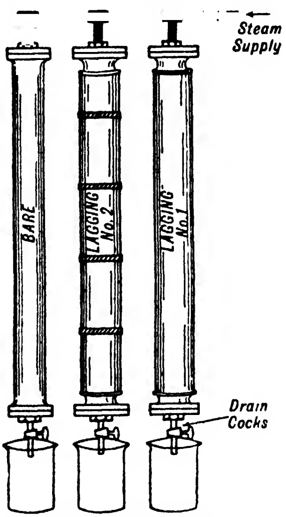


FIG. 39. Lagging Expt.

METHOD OF PROCEDURE. Steam is first passed through the tubes to bring them to the temperature of the steam supply before quantitative results are obtained. The drains are opened and all surplus condensation drained off, when the steam is allowed to flow into each of the pipes and remain for a time sufficient to allow a fair quantity of water to condense. This water is collected in separate containers and weighed. From the result a value for the condensation per square foot of pipe area can be obtained and the relative values of the lagging efficiencies determined.

A more exhaustive quantitative experiment may be taken if the condition of the steam before entry is determined by means of a throttling and separating calorimeter, and thus the heat losses per square foot can be determined for each form of pipe protection.

NOTE.—It should be understood that the object of lagging is to prevent the flow of heat from the interior of the pipe to the atmosphere, a flow which will occur normally due to the difference of heat

potential, or temperature between the steam and the atmosphere. This flow would, theoretically, continue until the temperatures inside and outside of the pipe were equal, but the existence of a heat insulator serves to prevent, to a large extent, this leakage of heat.

OBSERVATIONS.

Time for experiment =
Area of pipe in sq. ft. =
Weight of condensed steam in lb.:

(a) bare pipe =
(b) 1st lagging =
(c) 2nd lagging =

Weight of steam condensed per sq. ft. of pipe area:

(a) bare pipe = lb. per sq. ft.
(b) 1st lagging = lb. per sq. ft.
(c) 2nd lagging = lb. per sq. ft.

The results may then be put into the form of rate of condensation per square foot by introducing the time factor.

EXPT. 27. **Transfer of heat by convection.**

OBJECTS. *To show the method of transfer of heat in a liquid by convection currents.*

APPARATUS. A flask, retort stand, bunsen burner, and a few crystals of potassium permanganate.

METHOD OF PROCEDURE. Three-quarter fill the flask with water and scatter in the water a few crystals of the potassium permanganate, which will sink and later act as an indicator or colouring matter. Heat the water, when it will be noticed that the process of transfer of heat is by convection currents, that is, the hot water from the base of the flask will rise to the top, and the cold water from the top will sink to the bottom. This process continues until a uniform temperature is reached throughout the liquid. It should be noted that this is the process by means of which the water in a boiler is heated, and the condition

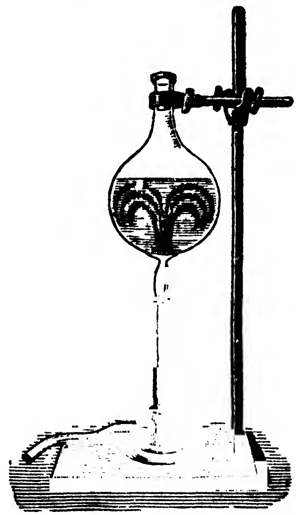


FIG. 40. Convection in a liquid.

of priming is brought about by the sediment in the boiler being carried to the top by the convection currents.

Since in convection the heat is transferred by the motion of the fluids themselves, the consequent mixing of the various currents eventually tends towards an equalisation of the temperature. The more rapid the movement of the water in boilers the more quickly can heat be transferred and steam generated. Hence the necessity in boilers to permit the easy upward flow of hot currents of water and bubbles of steam and the downward flow of relatively cold currents of water. Convection currents in the flue gases also play their part by removing gas particles which have been cooled by contact with the boiler tubes and replacing them by fresh hot particles of gas. Experiment No. 29 illustrates the convective flow of water and steam in a small model glass water tube boiler.

EXPT. 28. **Transfer of heat by radiation.**

OBJECTS. *To show that the radiation and absorption of heat from and by a black surface is greater than that of a polished surface.*

APPARATUS. Two calorimeters, one highly polished and the other blackened with a thin coating of lamp black.

METHOD OF PROCEDURE. Pour into each calorimeter equal quantities of cold water. Arrange the calorimeters at equal distances at the side of an iron plate, which is being heated by several bunsen burners. Leave the calorimeters in this position for 20 or 30 minutes, and then note the temperatures of the water in each calorimeter. It will be found that the blackened calorimeter has the higher temperature, thus having absorbed a greater quantity of heat. If these calorimeters be allowed to cool from equal temperatures when placed at a distance apart, the greater absorber will also be found the greater radiator, that is, the blackened calorimeter will cool more rapidly than the polished.

In the boiler radiant heat from the hot products of combustion reaches the tubes and drums in large quantities without heating the intervening gases, the energy being transmitted by wave motion in a similar way to light. Thus it will be seen that heat reaches the boiler by all three processes—conduction, convection and radiation. The heat so received passes through the walls of the tubes and to the water particles immediately in contact with them by conduction. Convection currents are then set up in the water and the temperature of the water gradually raised to boiling point, when steam generation begins in earnest.

This loss of heat by radiation is also evident in the auxiliary service pipes and cocks, and for this reason such pipes and cocks are kept polished.

The Lancashire boiler. A sphere would probably be the best form of vessel in which steam could be generated, but the cylindrical form

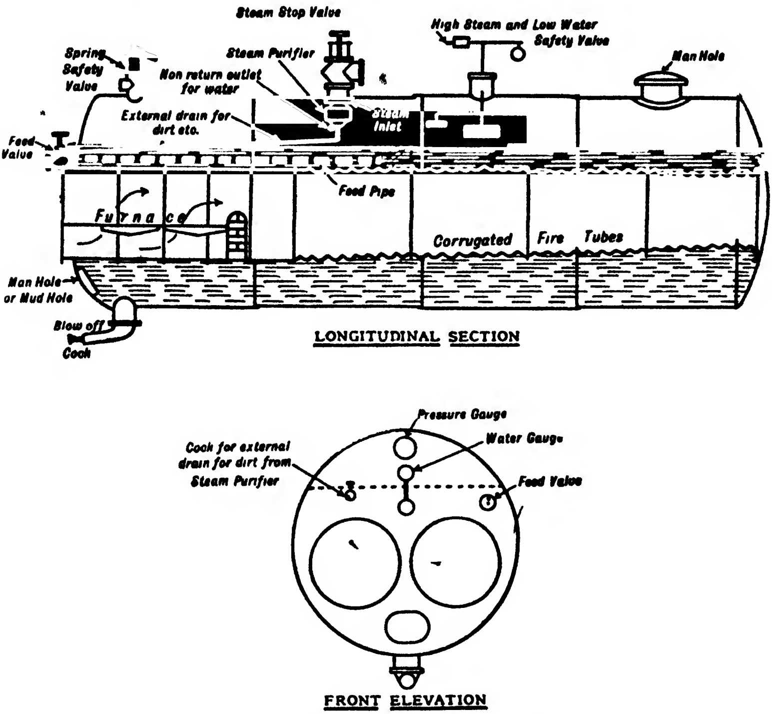


FIG. 41. Dish-end Lancashire boiler.

is more suitable, mechanically. The Lancashire boiler, invented by Fairbairn in 1840, is a typical boiler of the cylindrical shell type, and is the most generally employed of the stationary fire tube type. It possesses two internal furnace flues, and the largest sizes evaporate about 12,000 lb. of water per hour, being 30 ft. long and $9\frac{1}{2}$ ft. in diameter. Efforts have been made to overcome its defects of small combustion chamber volume and narrow flues by adopting forced

draught, air preheating and specially designed heat-resisting fire bars to cope with the higher temperatures. This has led to a much improved efficiency. Owing to the limitations placed on the thickness of the plates and the weight of the boiler, the pressure cannot exceed 200 lb. per sq. in.

Fig. 41 shows in purely diagrammatic form a dish-end Lancashire boiler and mountings. The boiler ends are pressed, dished and flanged in one operation, and the shape gives great strength and rigidity, obviating the use of stays and supports. Owing to the rigidity of these ends it is necessary to corrugate a portion of each of the two fire tubes so as to allow for expansion. The portion of the tubes containing the furnace is made straight. Air is admitted to each furnace above and below the grate, and the hot gases pass down the fire tubes and are then made to return along brick flues beneath the centre of the boiler. When the front of the boiler is reached, the gases are divided so as to pass along flues at each side of the boiler to the chimney, at the base of which a damper is fitted to control the flow of air. The supply of water to the boiler is pumped through the non-return feed valve to the perforated feed pipe within the boiler, the object of the holes and pipe being to carry, gradually, the new feed water as far into the boiler as possible. Manholes are fitted at the top and bottom of the boiler, large enough to admit men to effect cleaning and repairs. The other fittings are dealt with in more detail later in this chapter.

Water tube boilers. Boilers of this type are extremely popular for steam-raising for the following reasons :

(1) The component parts are comparatively light and can easily be put together, so avoiding high transport costs.

(2) They can be designed equally well for high or low pressures and for large or small evaporative power.

(3) Steam can be raised very quickly because of the rapid convective flow of water and the readiness with which heat can be transferred evenly to the bulk of the water.

(4) They can be easily adapted for mechanical stoking, pulverised or oil fuel firing, and mechanical ash removal, while the capacity and floor space are much less than with other types of boilers. In

fact, the boiler is less bulky in every respect than other types of the same power and there is a saving of space.

(5) Superheaters, economisers and air preheaters can be easily and economically incorporated in one compact unit, in which all parts are readily accessible.

These boilers have, however, the following disadvantages :

(1) The thin tubes are not so durable as the stouter shell of a Lancashire boiler, and they are liable to be choked.

(2) There are more small parts, and in consequence greater liability for small accidents and breakdowns.

(3) The internal pressure of the water tubes is more likely to cause accidents than the external pressure of fire tube boilers.

EXPT. 29.

OBJECT. *To study the transfer of heat in a model water tube boiler.*

APPARATUS. A model glass water tube boiler, as shown in Fig. 42, with provision for introducing an indicator, such as potassium permanganate, to illustrate the convection currents

METHOD OF PROCEDURE. The lower portion of the apparatus should be heated while immersed in a sand bath, thus producing an even distribution of heat over the length B, C, D. Fill the apparatus with water and introduce a small crystal of potassium permanganate into the top. As the water in the lower level B, C, D becomes heated it flows up the inclined tubes, and cold water from the top section flows to the bottom to take its place. The inclined tubes assist the convection currents, thus increasing the heating power of the boiler. It should be noticed that if the water in the top reservoir, which corresponds with the steam and water drum of a water tube boiler, were heated at A the heating effect would be confined to the water above A, because water is a poor conductor of heat, and that in the tubes would remain cold. The existence of the tubes produces convection currents, and a larger area in contact with the heating agent, thus increasing the heating power of the boiler.

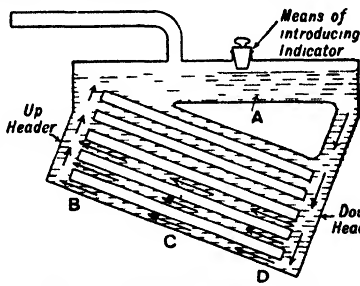


FIG. 42. Model W.T. boiler.

Fig. 43 shows a test boiler by Messrs. Babcock & Wilcox, which is capable of producing 40,000 lb. of steam per hour at 1575 lb. per sq. in.

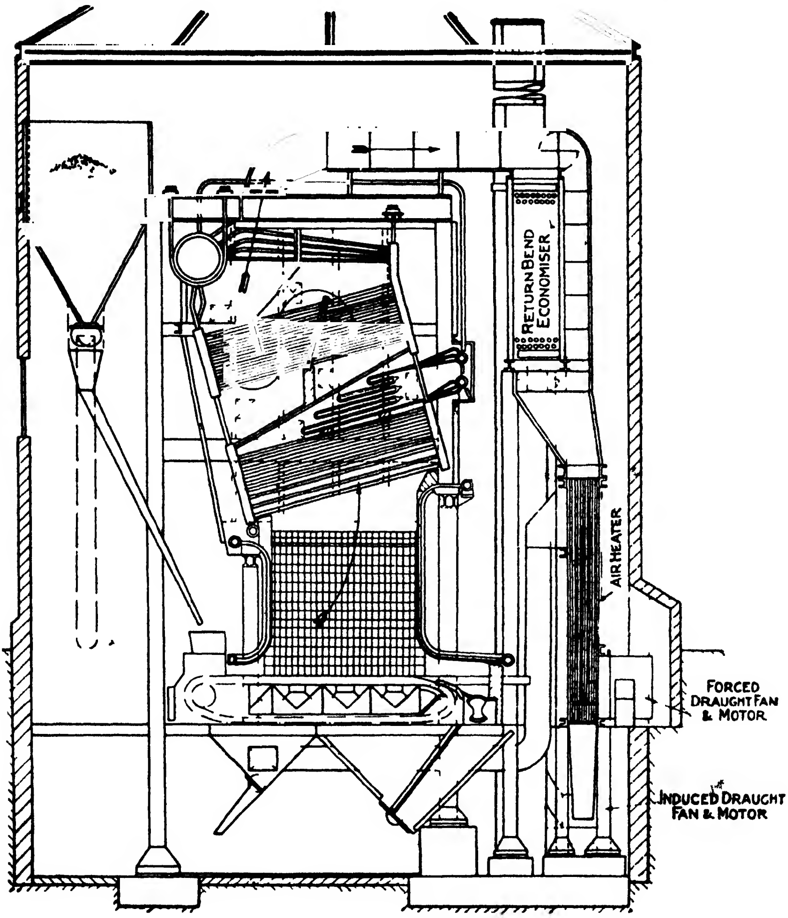


Fig. 43. Water tube boiler.

and 840° F. The fuel is supplied to the mechanical stoker from the hopper on the left and fired in a furnace of Bailey construction. This furnace is water-cooled to give the furnace walls longer life and

at the same time allow very high furnace temperatures, while the cooling-water, which is completely changed about every four minutes, forms an integral part of the boiler system. To the vertical cooling water tubes, metal blocks, ground to fit, are clamped, and these metal blocks are lined with refractory material, that is, material which is not easily fused or melted. The material is used as the bottom of the mould in which the block is cast.

The boiler itself comprises a nest of steel tubes which are connected directly to headers and these are connected by means of return tubes to a water and steam drum. These tubes are inclined at an angle of 15° to the horizontal and divided into two sections. The sections of the tubes are made up from solid drawn steel tubes expanded into solid drawn headers, or uptakes and downtakes at each end. An even distribution of furnace gases is ensured by staggering, so that every space in a horizontal row is covered by tubes immediately above or below in the next row. Every header is provided with hand holes opposite to each tube for ready access and cleaning purposes. The hand hole covers consist of internal oval hand hole caps, secured by an exterior dog and bolt and nut. A mud box collector is situated at the bottom of the headers at their lowest point.

The steam and water drum shown at the top of the figure is made of forged steel. The hot gases are made to pass at least three times between the tubes, being guided by baffle plates; the arrows indicate the path of the gases in the diagram. Convection currents are set up in the water in the tubes, the direction of flow being clockwise in the figure, hot water flowing upwards in the right-hand headers and being replaced by cold water coming down the left-hand headers. The circulation is thus rapid and positive, and conducive to the maintenance of an even temperature in the boiler. It is worthy of note that a large number of small tubes are preferable for steam-raising to a few large ones.

Sandwiched between the two sections of boiler tubes, and protected by the lower, the superheater will be seen, a series of S-shaped bends being given to the tubes. Steam for the superheater is drawn through a purifier from the top of the boiler water and steam drum.

After passing around the boiler drum and between the return

tubes at the top of the boiler, the furnace gases enter the flue and pass through the return bend economiser shown, and thence to the air preheater also marked. The gases then pass through the motor-driven induced draught fan and are discharged into the chimney

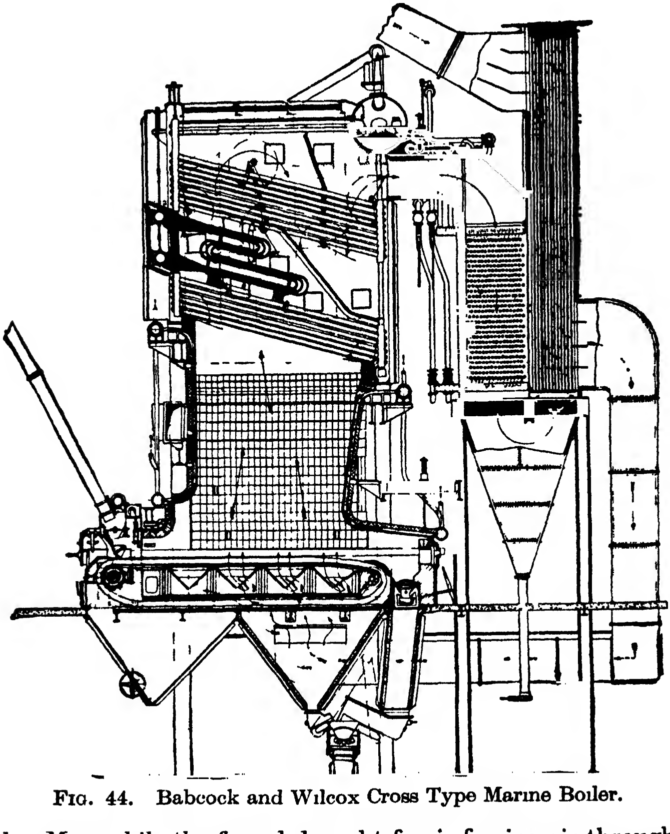


FIG. 44. Babcock and Wilcox Cross Type Marine Boiler.

stack. Meanwhile the forced draught fan is forcing air through the heater and through a duct to a point, marked with a cross, below the mechanical stoker. Here it is released with a high velocity, and passes through the burning fuel on the chain grate stoker. The two fans thus force and draw, in a balanced fashion, the air and products of combustion through the many obstacles placed in their way. The

flue gases may be by-passed so as not to pass through the economiser.

Fig. 44 shows a Babcock & Wilcox boiler fitted with interdeck superheater, forged steel return bend economiser, tubular air preheater with balanced draught chain grate stoker and Bailey water-cooled furnace. The diagram shows by dotted arrows the passage of the air supply through the preheater to the furnace, while the path of the products of combustion is shown by full line arrows through the furnace, boiler and superheater, economiser and air preheater to the chimney stack. Connections between the economiser and boiler drum are also shown, as are also the means for ash removal. Soot is collected in the hopper below the economiser and air heater.

This marine type of boiler has already been built in sizes up to a capacity of 800,000 lb. of steam per hour and for working pressures of over 1500 lb. per sq. in. The complete unit is enclosed in a steel casing protected where necessary by double plating, ensuring a minimum loss by radiation or of infiltration by cold air. Note the level of water in the boiler drum, and the steam in contact with the water from which it is being formed, thus providing the condition for the formation of saturated steam.

Pulverised fuel plant. A line diagram of one type of pulverised fuel plant is shown in Fig. 45. The coal or fuel has to be dried, ground to powder, then mixed with air and blown into the furnace through special burners. It is found that if the coal contains more than 4% moisture it binds and clogs pipes, mills, sieves, feeders, etc., and once the clogging action is started it tends to increase, and the entire plant may be put out of action. By keeping the moisture content below 1½% efficient working may be ensured. In the plant shown in the diagram the fuel enters the top of the drier, and is slowly oscillated or joggled over a series of baffle plates while hot flue gases from the boiler are blown upwards in the opposite direction. From the drier the fuel passes to the pulverising mill, where it is ground sufficiently fine for 68-70% to pass through a sieve containing 40,000 holes per sq. in., while 30-32%, that is the remainder, must pass through a sieve containing 2500 holes per sq. in. The attrition mills used for grinding are either of the ball or roller type while impact mills use a series of hammers.

When ground to a fine powder, a little compressed air is mixed with the fuel; this makes it become partially fluid, and it can be pumped considerable distances to storage bins and feeding hoppers. From the feeding hopper the dust gravitates to a feeder of the screw type which propels the dust to the mixer, where a supply of air meets the dust and forces it to the burners. The burners are arranged either horizontally or vertically to suit the height of the

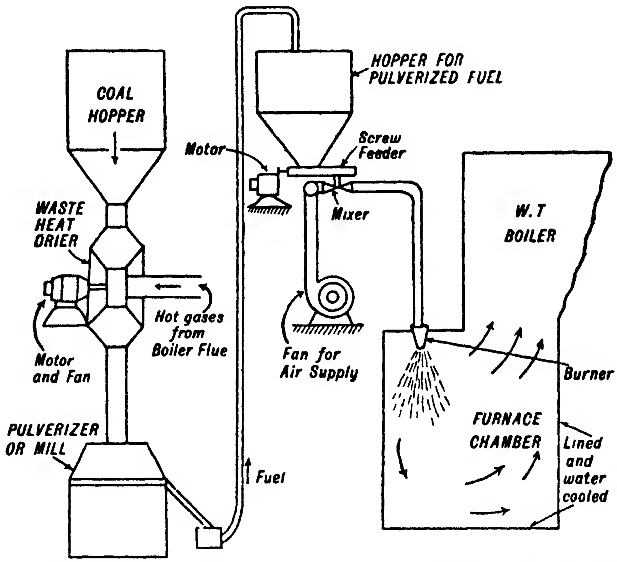


FIG. 45. Line diagram of a boiler fired by pulverised fuel (Fuller system).

furnace and to give a flame in the form of a ribbon, and to present as much surface as possible to the air supplied through regulators in the furnace walls. In this way the excess air is reduced to a minimum, which is a feature of a pulverised fuel furnace, but this type has the disadvantage of occupying about three times as much space as the ordinary coal-fired furnace with a mechanised stoker. The high combustion temperatures involved also need special water-cooled furnaces, but the cooling system forms part of the water tube system of the boiler. There is always a danger of explosions if the fuel is stored in bins.

The superheater has been devised to increase the temperature of steam without raising its pressure. In some cases superheaters are provided with their own furnace, but generally they are installed within the boiler setting, and the source of heat is the heat content of the flue gases from the boiler furnace. In the latter case they are called **integral superheaters.** This extra heat which the steam has gained helps to prevent wet steam being formed, due to temperature drop and radiation loss, while expanding in the prime mover. Dry steam means a lower consumption and better lubrication in the cylinders. The saving of from 15 to 25% in fuel consumption has led to the increasing use of superheated steam in engines and turbines.

The superheater is placed nearer the furnace than the economiser or air preheater, its actual position depending upon the degree of superheat required. It is usual to protect it by a few rows of boiler water tubes to prevent the tubes burning in the intense heat. To control the temperature an **attemporator** is sometimes used, by means of which excess heat may be passed to the feed water without loss to the system. Superheat temperatures up to 750° F. are used with steam turbines, and up to 500° F. with reciprocating engines.

All superheaters are designed, in essential matters, on the same principles. They consist of a number of small diameter steel tubes arranged to expose the desired amount of surface to the flue gases. A good design should conform to the following principles :

(1) Give rapid transference of heat from hot flue gases to steam.

(2) Be free from the danger of the tubes being burnt out. This is unlikely if the temperature is below 1000° F.

(3) Be easy of access and easy to clean.

(4) During a temporary stoppage, or while steam is being raised, it should be possible to cut off the hot gases from the superheater.

(5) Allowance should be made for the expansion of the pipes in making connections and fitting supports.

With highly superheated steam drop valves or piston valves work very satisfactorily, probably because the superheated steam behaves more as a gas.

The modern tendency is to superheat in stages, and the interdeck type of superheater is installed for this reason.

Prime movers are used to transform some of the heat energy of the working substance into mechanical energy. Prime movers employing steam may be divided into two classes:

(1) **Steam turbines,** which in principle are highly efficient windmills, where steam acts on the blades or vanes in the place of wind and produces a rotary motion of the rotor to which the vanes are secured.

(2) **Reciprocating engines** in which steam is expanded in cylinders, the expansion of the steam pushing a piston before it. Rotary motion is given to a shaft by means of a crosshead, connecting rod and crank (Fig. 36).

Economiser. This was devised to utilise some of the heat possessed by the hot flue gases before they are finally released to the stack. These gases have a temperature of about 650° F. in the case of shell boilers and about 525° F. in the case of water tube boilers. In heating the feed water this loss of heat is minimised, but a certain loss is inevitable, as the gases must always be at least 100° F. above the boiler water in order for transfer of heat to take place effectively. An economiser consists of a large number of tubes, connected by branch pipes or headers at the ends, through which feed water is pumped. The flue gases pass around the exterior of the tubes on the contra-flow principle and heat the water. In some recently designed economisers steaming is allowed, and the tubes are fitted with metal gills or fins to effect a more efficient heat transfer. Soot is systematically removed from the gills by a steam blower. A damper is often placed in the flue for the purpose of putting the economiser out of action when necessary, and as a precaution, safety and blow-off valves are fitted. These valves are described later in the chapter.

The advantages accruing from the employment of an economiser may be summarised as follows:

(1) A saving of from $\frac{3}{4}$ to 1 ton of coal in every 5 tons.

(2) The time required to convert water into steam is lessened, and the steaming capacity of the boiler is increased.

(3) Prevention of scale formation in boilers, because the scale forms in the economiser tubes which are more easily cleaned.

(4) Since hotter feed water enters the boiler the strains due to unequal expansion are minimised.

(5) The economiser provides hot water in plenty in the case of laundries, dye-works, breweries, where power together with a plentiful supply of hot water are required.

(6) While the temperature of the flue gases is roughly halved, that of the feed water may be raised through as much as 180° F.

(7) It is more economical to heat the comparatively cold feed water by relatively hot gases, where the temperature difference is high and transfer of heat therefore efficient, than to increase the boiler heating surface where the boiler contents are more nearly the temperature of the hot gases.

The disadvantages are :

(1) When the boiler pressure exceeds 350 lb. per sq. in., steel tubes must be used instead of cast iron or other metals. These steel tubes, being thinner, may be more quickly corroded if oxygen and carbon dioxide are present in the water.

(2) Soot forms on the tubes and must be removed, or heat transference is lessened.

(3) If the feed water is too cold as it enters the economiser it may condense the steam in the flue gases on to the outside of the tubes. This moisture, in conjunction with the sulphur dioxide in the gases, sets up a highly corrosive action, which the employment of a feed heater will prevent.

(4) Unless carefully designed the economiser will greatly lessen the draught through the boiler, because of the obstruction it sets up to the escape of flue gases. This may necessitate extra fan power.

EXPT. 30. **To illustrate the action of an economiser and the principle of contra-flow.**

OBJECT. *To show that the heating effect of flue gases is greater when the fluid subjected to heat is flowing in the opposite direction to the gases, that is, in contra-flow.*

APPARATUS. This consists of a sheet iron case fitted with baffles (Fig. 46), a gas ring and a suitable flue. The exterior is thoroughly lagged to prevent radiation losses. Into the interior of this case is fitted a rectangular copper container with water supply pipes A and B, each with a thermometer pocket and thermometer. Through the depth of the container a large number of copper fire tubes are fitted, so that the gases from the gas ring are taken through these

fire tubes to the flue in the direction indicated by the arrow. The whole container and pipes are made watertight, and thus become a model fire tube boiler. Water is supplied to this boiler through A or B, and taken out from A or B according to whether the flow is to be contra or otherwise. When contra-flow is required the water is supplied at a slow speed from a reservoir situated well above A, and

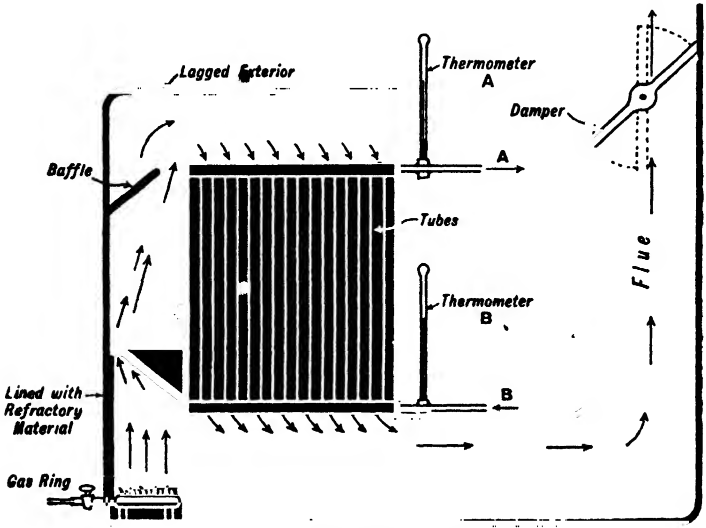


FIG. 46. Principle of contra-flow.

passes through B as inlet, flows against the direction of the flue gases, and is discharged from A into a reservoir situated below B. When uniflow, or flow in the same direction, is required, the pipes connected to A and B are interchanged; thus the water flows in at A and out from B.

METHOD OF PROCEDURE. Allow the water to flow very slowly in at A and discharge at B for a period of 20 min. Note the temperatures at A and B, and calculate the rise in temperature produced in uniflow. Next interchange the supply and discharge pipes at A and B, allow the apparatus to cool, and then repeat the experiment in contra-flow at the same speed of water service and for exactly the same time. Note the temperature rise between B and A, and compare it with the result obtained in uniflow.

CONCLUSION. It will be found that a greater rise of temperature

results from the contra-flow experiment, and this feature leads to the adoption of the principle of contra-flow in the design of air preheaters, gas calorimeters, waste heat boilers and economisers.

Air preheaters were introduced to abstract heat from the hot flue gases before these escaped to the chimney. As higher rates of evaporation and higher boiler pressures were being continually demanded, the flue temperature also became higher and higher, and therefore, to maintain a high boiler efficiency it was necessary to abstract a proportion of this heat in the products of combustion before allowing them to escape. Preheating of the air has also increased the efficiency of the boiler, because of (1) more rapid combustion and consequent greater furnace temperatures, and (2) more complete combustion, especially in the case of mechanical stokers, through there being less unburnt carbon in the ash.

The extent to which air should be preheated depends upon (1) the type of furnace and the highest temperature the materials composing it can withstand, without costly and frequent replacements, and (2) the highest temperature that the metal of the preheater can stand. The latter would be the controlling factor in the case of a water-cooled pulverised fuel or oil fuel furnace. The maximum temperature for mechanical stokers would thus appear to be 500° F.

The following factors should be considered with regard to increasing the efficiency of the air preheater :

(1) The design must be such as to produce the minimum obstruction to the flue gases, and hence the minimum loss of draught.

(2) The contra-flow principle must be adopted to produce the maximum heat transference from gases to air.

(3) The construction must permit of the minimum leakage.

(4) The preheater must be of such construction and in such a position as to allow of it being readily accessible for cleaning, while at the same time it must occupy as little space as possible.

Where economisers are also installed the amount of air-heating surface is usually about the same as the boiler-heating surface. Otherwise the air-heating surface is greatly in excess, and may be three or even four times as great as that for the boiler.

In the air preheater the hot flue gases and the cold air flowing in stream lines in opposite directions, and only separated by thin metal plates or tubes, make the transfer of heat extremely efficient and save 10% or more in the coal consumption.

Example. *On test, the following particulars were obtained from an air preheater of a steam power plant :*

Temperature of air entering heater $= 48°$ *F.*

Specific heat of air $= 0{\cdot}24$.

Temperature of gases entering heater $= 485°$ *F.*

Specific heat of gases $= 0{\cdot}25$.

Temperature of gases leaving heater $= 290°$ *F.*

Quantity of air $= 18{\cdot}6$ *lb. per lb. of fuel.*

Calorific value of coal used $= 13{,}900$ *B.Th.U. per lb.*

Assuming no heat losses, find the temperature of the air leaving the heater and the percentage of the calorific value saved.

Per lb. of fuel there will be $18{\cdot}6 + 1 = 19{\cdot}6$ lb. of flue gases.

Let t = final temperature of air.

Then heat lost by gases = heat gained by air.

$$19{\cdot}6 \times (485 - 290) \times 0{\cdot}25 = 18{\cdot}6 \times (t - 48) \times 0{\cdot}24,$$

$$t - 48 = \frac{19{\cdot}6 \times 195 \times 0{\cdot}25}{18{\cdot}6 \times 0{\cdot}24}$$

$$= 214\ ;$$

$$\therefore\ t = 262°\ \text{F.}$$

Heat energy saved = heat given to air $= 18 \times 214 \times 0{\cdot}24$ B.Th.U. per lb. of fuel.

$$\therefore\ \text{percentage of calorific value saved} = \frac{18 \times 214 \times 0{\cdot}24 \times 100}{13{,}900}$$

$$= 6{\cdot}65\%.$$

Chain grate stoker. These mechanical grates are designed to imitate hand-firing of the best kind. Usually the coking system (p. 5) is employed. Fuel is supplied uniformly through a hopper and spread across the width of the grate, and the latter moves slowly into the furnace. The grate is in the form of a wide endless chain

over pulley wheels driven by an electric motor through reduction gearing. Air can pass through the links of the grate, while the ash, etc., is thrown off at the back of the furnace down a shute to the ash removing plant. Some of the ash falls into the ash pit under the grate (as the bars or links are self-cleaning), because the coal is first coked at the front of the grate and is completely burnt by the time it reaches the back. These stokers have the advantages that no opening of fire doors is necessary, the moving grate keeps the fire clear, while a cheaper coal can be burnt efficiently. The speed of the grate is regulated so that complete combustion is achieved during the passage of the fuel from the front to the back of the furnace.

Example. *A steamship of* 12,000 *shaft horse power when mechanically fired consumed* 1·12 *lb. of coal (of calorific value* 13,500 *B.Th.U. per lb.) per shaft horse power per hour. When hand-fired the consumption had been* 1·22 *lb. per shaft horse power per hour. Calculate the thermal efficiency in each case.*

Also calculate, for mechanical firing : (a) the saving in fuel cost on a 21*-day journey when the fuel costs* 19*s.* 6*d. per ton.*

(b) The saving in bunker accommodation if 1 *ton of coal occupies* 45 *cu. ft.*

Mechanical firing :

$$\text{Thermal efficiency} = \frac{\text{heat converted into work at shaft per H.P. per hour}}{\text{heat supplied in fuel per H.P. per hour}}$$

$$= \frac{33{,}000 \times 60}{1{\cdot}12 \times 135{,}00 \times 778} = 16{\cdot}84\%.$$

Hand firing :

$$\text{Thermal efficiency} = \frac{33{,}000 \times 60}{1{\cdot}22 \times 13{,}500 \times 778} = 15{\cdot}45\%.$$

(*a*) Saving in fuel per H.P. per hour $= 1{\cdot}22 - 1{\cdot}12 = 0{\cdot}1$ lb.

$\therefore$ Saving in fuel per 12,000 H.P. per 21 days

$$= 0{\cdot}1 \times 12{,}000 \times 24 \times 21 \text{ lb.}$$

Saving in cost in £

$$= \frac{0{\cdot}1 \times 12{,}000 \times 24 \times 21 \times 19{\cdot}5}{2240 \times 20}$$

$$= £263\ 5s.\ 0d.$$

(*b*) Saving in bunker space in cu. ft.

$$= \frac{0{\cdot}1 \times 12{,}000 \times 24 \times 21 \times 45}{2240}$$

$$= 12{,}150 \text{ cu. ft.}$$

The condenser. The main function of a condenser is to condense the steam at as low a pressure as possible; it is especially important in turbines. This means that the latent heat of the steam must be abstracted at the pressure which exists in the condenser. There are four types of condenser, namely (1) the surface condenser, (2) the jet condenser, (3) the evaporative condenser, and (4) the ejector condenser. Space will allow of only the first type being dealt with; in the surface condenser the cooling water and the steam do not come into contact, and it is therefore of the type suitable for the closed feed system. The functions of this type of condenser may be summarised thus:

(1) To reduce by condensation the exhaust steam pressure and therefore the back pressure on the engine, and so allow economical expansion to the utmost limit.

(2) To return feed water to the boilers or feed heaters at as high a temperature as possible.

(3) To remove air from the condensate, and so obviate corrosion.

These functions are carried out efficiently in a modern condenser by paying particular attention to the following:

(1) The cooling water must be directed a definite number of times through the condenser to ensure a maximum temperature rise in order to keep the temperature of the condensate high.

(2) Steam must be allowed to circulate freely over the whole length of the tubes, and the condensed steam may be drained off to prevent it falling upon the lower ones.

(3) The pitch of the tubes must be greatest where the steam enters, and the flow area gradually reduced to give a constant steam flow through the condenser, the arrangement of the tubes being very important.

(4) A percentage (about 6%) of the tube surface should be baffled off near the water inlet, where air can collect and be pumped out while cool.

(5) The provision of an efficient air pump.

(6) The condenser casing must be airtight, otherwise the high vacuum condition demanded would not be obtained.

Fig. 47 shows the main parts of a surface condenser made by Messrs. Hick, Hargreaves & Co. The direction of flow of the cooling water is shown by the arrows. Water is pumped into the lower half of the water box end, and it flows through the tubes in the bottom half of the condenser to the return end, then through the tubes in the top half to discharge. In the section a number of the tubes are shown baffled off to cool the air, which can collect there ready to be pumped out through the outlet marked air suction. Exhaust steam from the prime mover enters at the top and flows over the cooling tubes, is condensed, and drops to the bottom of the condenser, where

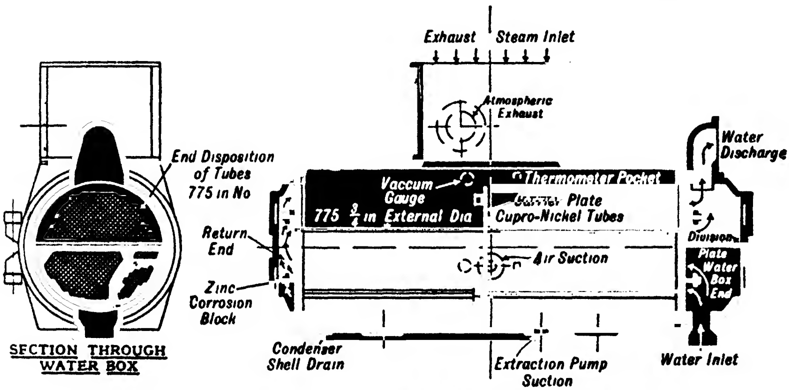


FIG. 47. A surface condenser (*Messrs. Hick, Hargreaves & Co*).

it is extracted by a pump through the orifice shown. The **condensate extraction pump** is usually of the centrifugal type. Provision is also made for exhausting the steam directly to the atmosphere, as indicated on the diagram. Since the zinc can be easily replaced, four zinc corrosion blocks are mounted on the tube plates at both the water box and return ends of the condenser with the object of saving the tubes and plates from electrolytic action (see p. 282). It is found that especially where sea water is used for cooling, aerated sea water forms the electrolyte between the tubes and the condenser ends, causing corrosion of the latter in the absence of the zinc blocks.

Regenerative condenser is the name given to that type of condenser designed to prevent, as far as possible, the temperature of the condensate falling below that of the incoming steam. In most con-

densers the condensate is cooled by coming into contact with the cold tubes at the bottom of the condenser. This results in a lower boiler feed temperature and considerable waste of fuel and energy. With the regenerative condenser the incoming steam is allowed to penetrate freely to the bottom of the condenser and reheat the condensate before it is withdrawn.

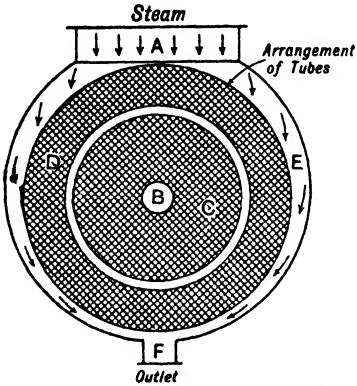


Fig. 48. A regenerative condenser.

Fig. 48 shows a section of a regenerative condenser of the Westinghouse type, in which the cooling tubes are arranged in two groups C and D, concentric with each other but not with the condenser shell. The air is withdrawn at B after being cooled by the cold inner group of tubes C, while the condensate is taken from F at a temperature approximately that due to the vacuum in the condenser. The outer belt of tubes D are warmer, due to contact with the steam, and the condensate has to pass over these before it is withdrawn. There is also very little alteration of pressure between the inlet at A and the air outlet at B due to the short radial flow of the steam towards B.

Jet condensers employ a water spray arranged to meet the exhaust steam as it enters the condenser. Thus the steam and cooling water mix intimately with the attendant disadvantages of introducing air and impurities to the condensate.

Example 1. *In a jet condenser 20 lb. of cooling water at 50° F. are injected to condense each lb. of steam of dryness fraction 0·9 at 212° F. What is the final temperature of the mixture ?*

Total heat per lb. of wet steam $= 180 + 970 \times 0{\cdot}9$ or 1053 B.Th.U.

Let $t°$ F. be the final temperature, then

$$\text{heat gained by water} = \text{heat lost by steam.}$$

$$20 \times (t - 50) \times 1 = 1053 - (t - 32).$$

$$20t - 1000 = 1053 - t + 32.$$

$$21t = 2085.$$

$$t = 99{\cdot}3. \quad \textbf{Ans. 99·3° F.}$$

Example 2. *A condensing engine developing 250 B.H.P. converts 12% of the energy of the coal into B.H.P. and 55% is discharged in the circulating water, which rises 42° F. in temperature when supplied to the surface condenser. What weight of cooling water must be supplied?*

12% of the energy corresponds to 250 × 33,000 or 8,250,000 ft. lb. per minute.

$$\therefore \; 55\% \text{ of the energy corresponds to } \frac{8{,}250{,}000}{12} \times 55 \text{ ft. lb. per min.}$$

$$= \frac{37{,}812{,}500}{778} \text{ or } 48{,}602 \text{ B.Th.U. per min.}$$

Wt. of water per min. × temp rise × specific heat = 48,602.

$$\therefore \; \text{Wt. of water per min. in lb.} = \frac{48{,}602}{42 \times 1} = 1157.$$

Example 3. *A parallel flow jet condenser, in which the steam and water enter at the same end of the condenser and flow in the same direction, is required to condense* 15,000 *lb. of steam per hour when exhausted from a turbine, and to maintain a vacuum of* 28·06 *in.* (0 95 *lb. per sq. in. abs.*) *when supplied with cooling water at* 70° *F. The injection water temperature at outlet is not to be more than* 4° *F. below the steam temperature at inlet. Calculate the number of gallons of injection cooling water required per minute.*

Temperature of steam at inlet at 0·95 lb. per sq. in. abs.

= 100° F. (from tables).

∴ Temperature of injection water at outlet = 100° F. − 4° F. = 96° F.

Temperature of injection water at inlet = 70° F.

∴ Temperature rise = 96° − 70° = 26 Fahr. degrees.

Latent heat given up per lb. of steam = 1033·8 B.Th.U. (from tables).

N.B.—It is not desired to remove any sensible heat, except the unavoidable drop of 4 degrees from 100° F. to 96° F.

$$\therefore \; \text{Injection water required for cooling} = \frac{1037{\cdot}8 \times 15{,}000}{26}$$

= **997·7 gallons per min.**

Example 4. *In a preliminary design for a power plant it was known that the steam consumption was to be 40,000 lb. per hour and the cooling water available in the summer months 2875 gallons per minute at a mean temperature of 60° F. Estimate the probable vacuum obtainable, assuming 1000 B.Th.U. abstracted per lb. of steam and the difference of temperature between the steam entering the condenser and the cooling water leaving it as 8° F.*

Let t = final temperature of cooling water.

Heat lost in steam = heat gained by water per hour.

$$40{,}000 \times 1000 = 2875 \times 10 \times 60 \times (t - 60).$$

$$t - 60 = 23{\cdot}19° \text{ F.};$$

$$\therefore\ t = 83{\cdot}19° \text{ F.}$$

$\therefore$ Temperature of steam entering condenser $= 83{\cdot}19° + 8° = 91{\cdot}19°$ F. By using steam table values and plotting a graph it will be found that this temperature corresponds to an absolute pressure for steam of 0·74 lb. per sq. in., or to a vacuum of 28·52 in.

Example 5. *Find the volume of air and condensate which must be removed per minute from a condenser in which the steam condensed is 100,000 lb. per hour and the vacuum and temperature at the point of pump suction being 28·26 in. and 90° F. respectively. The weight of air removed is estimated at 53 lb. per hour. Vacuum corresponding to a steam temperature of 90° F. is 28·57 in. Take R for air as 53·2 ft. lb. per lb. per Fahr. degree. Barometer 30 in. of mercury.*

Total pressure due to steam and air inside condenser

$$= 30 - 28{\cdot}26 = 1{\cdot}74 \text{ in. of mercury.}$$

Steam or vapour pressure at point of pump suction

$$= 30 - 28{\cdot}57 = 1{\cdot}43 \text{ in. of mercury.}$$

$\therefore$ Pressure due to air at point of pump suction

$$= 1{\cdot}74 - 1{\cdot}43 = 0{\cdot}31 \text{ in. of mercury.}$$

Using the relation $PV = wRT$ to find V, where

$P = 0{\cdot}31 \times 0{\cdot}49 \times 144$ lb. per sq. ft. abs., since 1 in. of mercury is equivalent to 0·49 lb. per sq. in.,

$w = 53$ lb., $R = 53{\cdot}2$ ft. lb. per lb. per Fahr. degree,

$T = 460° + 90° = 550°$ F. abs.

Then $$V = \frac{wRT}{P} = \frac{53 \times 53{\cdot}2 \times 550}{0{\cdot}31 \times 0{\cdot}49 \times 144} = 70{,}890 \text{ cu. ft. per hour}$$

$$= 1181{\cdot}5 \text{ cu. ft. per min.}$$

Volume of condensate to be removed, since 1 cu. ft. of water weighs **62·3 lb.,**

$$\frac{100{,}000}{60 \times 62{\cdot}3} = 26{\cdot}75 \text{ cu. ft./min.}$$

N.B.—This calculation provides the preliminary data from which the necessary size of pump can be found.

Boiler fittings and mountings. These may be divided into two categories, namely, those for the direct control of steam generation and those which come into play automatically for safety purposes should the human element fail. It is proposed to deal with the two types in the order mentioned.

The feed check valve. This controls the flow of feed water to the boiler, and must act as a check or non-return valve capable of working at considerably higher pressures than the maximum boiler pressure. Usually the valve is of the mushroom type (see Fig. 110), its opening controlled by a hand wheel through a screw and rod, although not connected to it. The higher pressure of the feed water on the pump side of the valve lifts it the amount allowed by the rod, and the feed water flows into the boiler. Any flow in the reverse direction would force the valve back on to its seating, and so prevent any escape of boiler steam or water should the feed pump break down or a burst occur in the feed pipe.

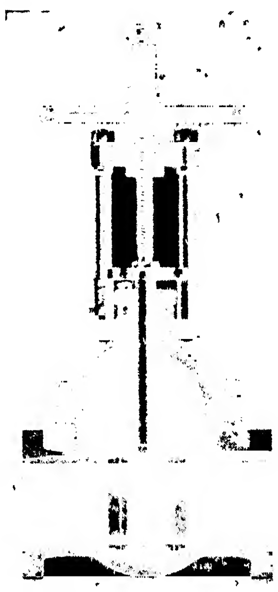


Fig. 49. Parallel slide stop valve.

The pressure gauge. The usual type of gauge employed has already been described (p. 32), and it indicates the gauge pressure in the boiler to the attendant whose duty it is to maintain the pressure necessary to meet the requirements in the engine room.

The stop-valve. This is used to regulate the supply of steam from the boiler to meet the demand made by the engine. Fig. 49 shows

a patent parallel slide stop-valve made by Messrs. Hopkinsons, Ltd., the type shown having a rising spindle. The main feature of this kind of stop-valve is that it gives a full bore, that is, an uninterrupted passage for steam through it. It is provided with parallel valve faces formed by means of a pair of parallel discs free to rotate on their axes, and to work between, and bed on, parallel seats in the steel body of the valve. The spring between the discs keeps them on their seats when the valve is not under pressure, and so prevents any foreign matter lodging in such a way as to stop the valve closing. The valve facings and seats are made of Hopkinsons' platnam, a special alloy capable of resisting hard wear and corrosion. Rotation of the hand wheel causes the valve to open or close, and the sliding crosshead, made of malleable iron, can be fitted with an indicator to show the amount of valve opening. The two pillars and bridge, which support the threaded valve rod of stainless steel, are made of mild steel and finished bright. The two pillars form slides for the crosshead. This valve is made for steam pressures up to 450 lb. per sq. in. and temperatures up to 800° F.

An isolating or non-return valve is generally fitted near the stop-valve to prevent the accidental admission of steam from other boilers, when a number of these are connected to the same steam pipe, and when one is empty and undergoing repair. Combined stop and isolating valves are sometimes used.

Blow-off valve. The function of this valve is to permit the boiler being emptied when necessary, and it can be used for blowing out the solids or sediment which accumulate at the bottom of the boiler. When the valve is opened the high pressure forces water out with a high velocity, and this water carries some of the solid matter with it; it must therefore be placed below the boiler drum and connected to the bottom of the latter. In construction it may be of the parallel slide type as just described, but it is usually operated by a hand lever which rotates a pinion meshing with a rack formed on the valve spindle.

Dampers. These are valves or sliding doors placed in the flues to regulate the flow of gases or draught, and thus control the intensity of combustion and the rate of steam generation.

EXPT. 31.

OBJECTS. (*a*) *To examine the action of the draught in a model chimney.*

(*b*) *To show the effects of dampers and baffles in the control of flue gases.*

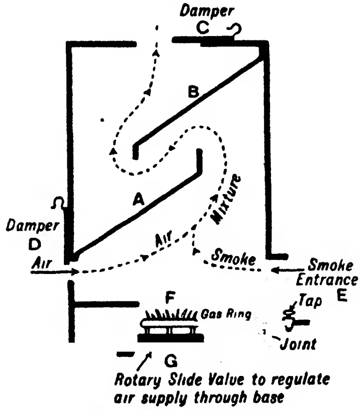


FIG. 50. Expt. 31.

APPARATUS. This consists of a metal casing with a glass front (Fig. 50). To the casing is fitted a pair of baffles A and B, and a top and bottom damper C and D respectively. There is a smoke entrance at E, a source of heat at F, and a rotary slide valve to regulate any air supply required through the base at G.

METHOD OF PROCEDURE. When heat is applied at F and the dampers C and D opened convection currents of air pass from the hot region at F, and are directed by the baffles A and B to the cold region around the outlet C. If C is open these hot gases pass out into the atmosphere, but if C is kept closed they recirculate, falling to the lower level as they cool, and are replaced by the hot gases or air from the hot region. If some smoke is introduced through E the effects of various damper or air supply openings may be observed through the glass screen, and the directing influence of the baffles noticed.

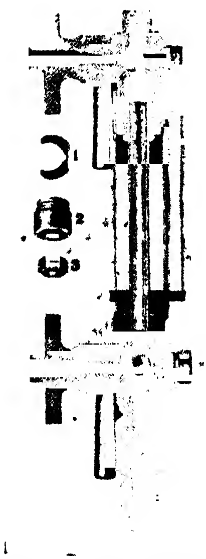


FIG. 51. Water gauge.

Water gauge, or gauge glasses. To indicate the water level in the boiler drum a water gauge is employed, the level being visible in a glass tube. Fig. 51 shows a patent water gauge by Messrs. Dewrance & Co., provided with an automatic ball valve in the lower water arm and a patent automatic spring valve in the top steam arm. Three cocks are also provided, the steam, the water and the blow-through cock at the bottom, and all three are

made tight by a system of asbestos packing in which the cock revolves without touching the metal. Should the glass tube break under pressure the ball in the lower arm rises to its seat and prevents the escape of water. At the same time the outward rush of the steam to the top arm pushes the spring in the top arm against a seating and shuts off the steam. To ensure that the gauge is registering correctly it is occasionally blown through, first by opening the

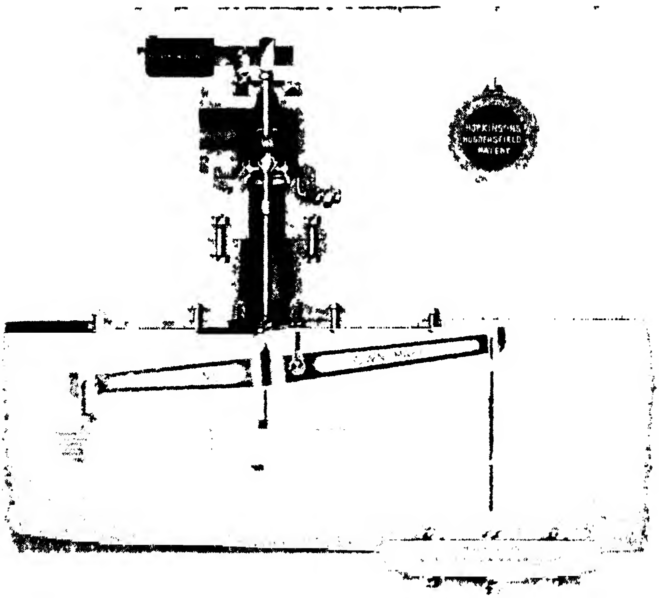


Fig. 52. Duad safety valve and low water alarm.

blow-through cock at the bottom and then by opening and shutting the steam and water cocks in turn. This clears the passages of any sediment which might have accumulated. The spring valve in the top arm is, however, strong enough to stop the valve closing when blowing through, and the type of gauge shown is suitable for ordinary conditions and pressures. Gauge glasses are easily replaced, and the joints easily broken by the patent lifter shown. Thick glass and wire mesh protectors are often fitted around the glass tubes of the gauges.

The fittings of an automatic nature fitted as safety devices will now be considered.

Combined safety valve and low water alarm. This safety device, shown in Fig. 52, is largely adopted as a mounting for Lancashire and similar boilers. The valve block contains two valves, the larger acting as a seat for the smaller ball valve, the spindle of which carries the central dead load. Thus as the larger valve supports the external lever, it is kept on its seat by the combined dead weight and loaded lever. The large valve blows and allows steam to escape when the steam pressure on the base of the valve is sufficient to overcome this combined load. In this way the attendant receives warning by the sound of the large valve blowing. When the water in the boiler drops below a certain level the float shown on the right of the illustration drops with it and turns the balanced lever clockwise about its fulcrum. The latter is shown to the right of the hollow boss on the lever through which the dead load spindle passes. As the lever turns, projections on the top of the boss come into contact with a collar on the valve spindle, which is raised, lifting the ball valve off its seat. Further rotation of the lever will take the remaining load off the big valve, and both valves will lift and give audible warning. The sound of blowing by the ball valve is clearly distinguishable from that of the large valve.

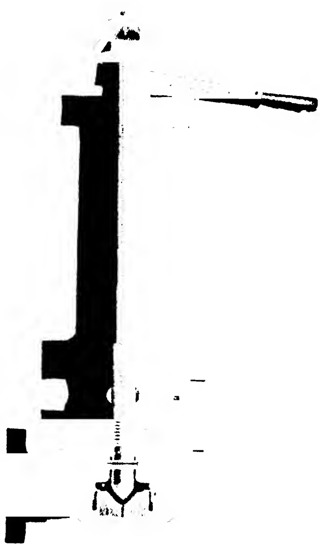


Fig. 53. Spring loaded safety valve.

There are three common methods of loading safety valves, namely, by loaded lever, by a dead weight on the spindle, or by means of a spring. A spring loaded safety valve is illustrated in Fig. 53. and is designed for boilers generating steam up to 450 lb. per sq. in. by Messrs. Hopkinsons, Ltd. The valve, made of platnam, is guided both

above and below its seat, while the rod is of stainless steel. Spring plates at the top and bottom of the steel spring prevent it from buckling and keep the valve on its seat. For high pressures the body of the valve is made of cast steel. If the pressure on the valve is within 50 lb. of the maximum spring load, the easing lever at the top can be used to lift the valve from its seat. Often pilot safety valves are fitted to give warning in big installations by blowing off slightly before the main safety valves, and allowing the attendants to adjust matters and so economise steam.

Fusible plugs are fitted on the furnace crowns and bases of boiler drums, and their object is to allow water and steam to escape and put the fire out should, by any accident, the water level become dangerously low. They contain metal of comparatively low melting point, which fuses at a known temperature and so provides an outlet in the event of this temperature being reached.

To remove moisture and impurities from steam a **steam purifier** may be used, and it may be placed either inside the boiler just before the exit or in the pipe line. The steam is given a rapid spiral motion by means of vanes, and the strong centrifugal action set up throws the heavier particles of water or dirt on to the sides of the purifier, from which they may be drained and collected. Appliances used for the purpose of drying steam are commonly called **steam separators** or **traps.**

Boiler calculations. The **thermal efficiency of a boiler** is the ratio

$$\frac{\text{heat given to produce steam per lb. of fuel}}{\text{calorific value of fuel}}.$$

The **evaporative capacity or power** of a boiler is the weight of water in lb. per hour that it can evaporate. Frequently reference is made to the term **evaporation per lb. of fuel.** These terms are, however, vague unless the feed temperature and final steam pressure and temperature are specified. If in a given boiler the heat actually given to the feed water per lb. of fuel were employed to raise a certain weight of water at 212° F. to steam at a pressure of 14·7 lb. per sq. in., this certain weight of water is called the **equivalent evaporation.** It provides a means of comparing the true performance of boilers. Since the heat to convert 1 lb. of water at 212° F. into steam at atmos-

pheric pressure is 970 B.Th.U. (or 539 C.H.U.), then if B.Th.U. are employed, equivalent evaporation

$$= \frac{\text{heat in steam above feed temp. per lb. of fuel used}}{970}.$$

The factors affecting the evaporative power of boilers can be summarised under three headings.

(*a*) The heat required to produce 1 lb. of steam. This depends upon the initial feed temperature and the final pressure and degree of superheat of the steam.

(*b*) The quantity and quality of the fuel burnt per hour. The quantity depends upon the grate area and the draught, while the calorific value of the fuel is a measure of its quality. The quality and quantity of the fuel burnt control the intensity of heat produced by combustion.

(*c*) The design and condition of the boiler. These factors control the effectiveness of the heat transference through the walls of the tubes and drums, since this effectiveness depends upon the thickness of those walls, their conductivity, and the difference of temperature on the two sides.

Example 1. *A boiler, with economiser, raises* 8·2 *lb. of water per lb. of coal from a feed temperature of* 170° *F. to steam at a pressure of* 500 *lb. per sq. in. (absolute) and temperature of* 700° *F. Find the total heat of the steam per lb. above feed temperature and the equivalent evaporation, given that the mean specific heat of the steam is* 0·63.

From tables, temperature of saturated steam at 500 lb. per sq. in.

$$= 467{\cdot}1° \text{ F.}$$

Degree of superheat $= 700 - 467{\cdot}1 = 232{\cdot}9°$ F.

Total heat of steam above feed temp. (from tables) per lb.

$$= 1213{\cdot}2 + 232{\cdot}9 \times 0{\cdot}63 - 138 = \mathbf{1221\ B.Th.U.}$$

Heat in steam above feed temp. per lb. of fuel used

$$= 8{\cdot}2 \times 1221 = 10{,}012 \text{ B.Th.U.}$$

Therefore equivalent evaporation $= \dfrac{10{,}012}{970} = \mathbf{10{\cdot}32\ lb.}$

Example 2. *A steam turbine requires 66,000 lb. of steam per hour, and the evaporative power of the Scottish coal to be used may be taken as 7·8 lb. per lb. of fuel. Taking the rate of combustion of the grate as 26·3 lb. of coal per sq. ft. of grate per hour, estimate the area of grate required.*

$$\text{Wt. of fuel to be fired per hour} = \frac{66{,}000}{7 \cdot 8} = 8461 \cdot 5 \text{ lb.}$$

$$\text{Therefore area of grate wanted} = \frac{8461 \cdot 5}{26 \cdot 3} = \mathbf{322 \text{ sq. ft.}}$$

Example 3. *In a 4 hours' trial of a water tube boiler 6500 lb. of oil were burnt in evaporating 89,360 lb. of water from feed water at 80° F. to dry saturated steam at 250 lb. per sq. in. (absolute). The calorific value of the Russian fuel oil used was 19,400 B.Th.U. per lb. Determine the boiler efficiency and the equivalent evaporation.*

$$\text{Water evaporated per lb. of fuel} = \frac{89{,}360}{6500} = 13 \cdot 75 \text{ lb.}$$

Heat in steam per lb. above feed temp. (from tables)

$$= 1207 - 48 = 1159 \text{ B.Th.U.}$$

$$\text{Heat transferred to water per lb. of fuel} = 1159 \times 13 \cdot 75$$

$$= 15{,}936 \text{ B.Th.U.}$$

$$\text{Boiler efficiency} \quad \frac{15{,}936}{19{,}400} \times 100 \quad 82\%.$$

$$\text{Equivalent evaporation from } 212° \text{ F.} = \frac{1159 \times 13 \cdot 75}{970} = \mathbf{16 \cdot 4 \text{ lb.}}$$

Example 4. *A Lancashire boiler taking feed water at 150° F. supplies all its steam at 250 lb. per sq. in. abs. and 0·97 dry to engines developing 630 H.P. The coal consumption is 1400 lb. per hour and the calorific value of the coal 12,100 B.Th.U. per lb. If the engines take 18·5 lb. of steam per H.P. hour calculate :*

(a) *the efficiency of the boiler :*

(b) *the indicated thermal efficiency of the whole plant.*

Heat in steam at 250 lb. per sq. in. abs. and 0·97 dry reckoned above 32° F. as datum $= 376 \cdot 3 + 0 \cdot 97 \times 830 \cdot 7 = 1182 \cdot 1$ B.Th.U. per lb.

$$\text{Heat per lb. supplied by boiler above } 150° \text{ F.} = 1182 \cdot 1 - 150 + 32$$

$$= 1064 \cdot 1 \text{ B.Th.U.}$$

$$(a) \text{ Boiler efficiency } = \frac{\text{heat supplied by boiler per H.P. hour}}{\text{heat supplied to boiler per H.P. hour}}$$

$$= \frac{1064 \cdot 1 \times 18 \cdot 5 \times 630}{12{,}100 \times 1400} = 0 \cdot 732 \text{ or } \mathbf{73 \cdot 2\%}.$$

(b) Overall efficiency $= \dfrac{\text{heat converted into indicated work per hour}}{\text{heat supplied per hour}}$

$$= \frac{630 \times 33{,}000 \times 60}{12{,}100 \times 1400 \times 778} = 0\cdot0946 \text{ or } 9\cdot46\%.$$

Example 5. *The following details concern a steam plant generating 16,800 lb. of steam per hour.*

	Heating Surface.	
Economiser.	1600 *sq. ft.*	*Feed water raised from* 80° *F. to* 200° *F.*
Boiler.	3200 *sq. ft.*	*Steam leaves* 0·98 *dry at* 250 *lb. per sq. in. abs.*
Superheater.	1700 *sq. ft.*	*Steam leaves at* 250 *lb. per sq. in. abs. and* 721° *F.*

Calculate the rate at which heat is being transmitted in B.Th.U. per sq. ft. per hour in each of the above sections of the generating plant and the probable fuel consumption per hour if the efficiency of the plant is 78%. *Calorific value of fuel used* = 13,500 *B.Th.U. per lb.*

Heat in steam per lb. above datum 32° F. as steam leaves boiler

$$= 376\cdot3 + 0\cdot98 \times 830\cdot7 = 1190\cdot4 \text{ B.Th.U.}$$

Heat gained in economiser per hour $= 16{,}800 \times (200 - 80)$

$$= 2{,}016{,}000 \text{ B.Th.U. per hour.}$$

Heat gained in economiser per hour per sq. ft. of heating surface

$$= \frac{2{,}016{,}000}{1600} = \mathbf{1260 \text{ B.Th.U.}}$$

Heat gained in boiler per hour per sq. ft. of heating surface

$$= \frac{(1190\cdot4 - 200 + 32) \quad 16{,}800}{3200} \text{ B.Th.U.}$$

$$= \mathbf{5367\cdot6 \text{ B.Th.U.}}$$

Heat in superheated steam with a saturation temperature of 401° F. and a degree of superheat of 721° − 401° or 320 Fahr. degrees from tables = 1385·5 B.Th.U. per lb.

∴ Heat gained in superheater per hour per sq. ft. of heating surface

$$= \frac{(1385\cdot5 - 1190\cdot4) \times 16{,}800}{1700} \text{ B.Th.U.}$$

$$= \mathbf{1928 \text{ B.Th.U.}}$$

Heat required per hour above feed temperature

$$= (1385\cdot5 - 80 + 32) \times 16{,}800 \times \frac{100}{78} \text{ B.Th.U.}$$

∴ estimated fuel consumption

$$= \frac{1337\cdot5 \times 16{,}800}{13{,}500} \times \frac{100}{78} = \mathbf{2133 \text{ lb. per hour.}}$$

Example 6. *Fuel used in a boiler plant had the following composition by weight, C 84%, H 15%. When 60% excess air at 60° F. was supplied, what was the proportion of total flue gas loss of heat at the chimney that was due to excess air? Temperature of flue gases at entrance to chimney = 530° F.: specific heat of air = 0·24 and of flue gases 0·26.*

Minimum air required per lb. of fuel

$$=\frac{100}{23}(0{\cdot}84\times 2\tfrac{2}{3}+0{\cdot}15\times 8)=14{\cdot}955 \text{ lb.}$$

∴ Wt. of flue gases per lb. of fuel if ash content is ignored

$$=14{\cdot}955+1 \text{ lb.}$$

Heat lost in flue gases per lb. of fuel

$$=(14{\cdot}955+1)\times(530^\circ-60^\circ)\times 0{\cdot}26$$
$$=1950 \text{ B.Th.U.}$$

Wt. of excess air = 60% of 14·955 lb. = 8·973 lb.

Heat lost in excess air per lb. of fuel $=8{\cdot}973\times(530-60)\times 0{\cdot}24$
$=1012$ B.Th.U.

Percentage loss in excess air $=\dfrac{1012}{1012+1950}\times 100=34{\cdot}2\%$.

Example 7. *A turbine steamer is to be supplied with boilers for engines which develop 6000 H.P. The boilers are to generate steam at 400 lb. per sq. in. abs. and 140 Fahr. degrees of superheat from feed at 140° F. using coal with a calorific value of 14,200 B.Th.U. per lb.*

Assuming that a firing rate of 22 lb. of coal per sq. ft. of grate area is permissible, that the engine consumption is 13 lb. of steam per H.P. hour, and that the efficiency of the boiler and superheater is 78%, calculate the total grate area required.

For an overload output of the boiler the firing rate may be increased to 28 lb. per hour per sq. ft. of grate area. Calculate this overload output if the boiler efficiency drops to 70%.

Heat in steam at 400 lb. per sq. in. abs. and 140 Fahr. degrees of superheat, from tables = 1301·7 B.Th.U. per lb. above 32° F.

∴ Heat required per lb. of steam

= 1301·7 − 140 + 32, since 140° F. is the feed temperature,
= 1193·7 B.Th.U.

Steam consumption = 6000 × 13 = 78,000 lb. per hour.

Heat per hour required $=1193{\cdot}7\times 78{,}000\times\dfrac{100}{78}$

= 119,370,000 B.Th.U.

Weight of coal required per hour $= \dfrac{119{,}370{,}000}{14{,}200}$ lb.

$\therefore$ grate area required $= \dfrac{119{,}370{,}000}{14{,}200 \times 22} = \mathbf{382 \cdot 1}$ **sq. ft.**

On overload, heat usefully employed per hour $= 382 \cdot 1 \times 28 \times 14{,}200 \times 70/100$ B.Th.U.

$\therefore$ weight of steam generated $= \dfrac{382 \cdot 1 \times 28 \times 14{,}200 \times 70}{1193 \cdot 7 \times 100}$

$=$ **89,100 lb. per hour.**

EXERCISES ON CHAPTER III

Steam generating plant.

1. Name the principal and minor components of a steam power plant, and state briefly the function of each.

2. Why is it necessary to keep the working substance pure in a steam power plant, and what are the steps taken to accomplish this ?

3. Sketch and describe a Lancashire boiler, and state its advantages over other types.

4. Why is make up feed water necessary in a steam plant ? How can the supply be arranged ?

5. Make a list of the boiler fittings necessary to equip a Lancashire boiler, and state in a few words the function of each.

6. Describe a water tube boiler, and state what advantages it possesses over a Lancashire boiler.

7. What are the advantages of heating the feed water to a boiler, and how can it be accomplished ?

8. Describe the function and chief features of a good design of integral superheater.

9. What is the object of heating the air supply to a furnace, and how is it done ?

10. State the advantages and disadvantages of water tube boilers and fire tube boilers.

11. Describe with the help of sketches a boiler stop valve. What other types of valve are necessary for a water tube boiler ?

12. State the fittings of an automatic nature employed to avoid accidents in boilers, and sketch and describe one of them.

13. Describe in a water tube boiler how the three modes of heat transference, namely, conduction, convection and radiation, are employed to convey heat from the burning fuel to the water.

14. What are the chief causes of the production of smoke in boilers, and how should a furnace be managed to reduce the smoke as far as possible?

15. Explain why it is necessary to adjust the thickness of the fire and the speed of a mechanical grate so that the fuel is completely burnt and the heat loss in the flue gases and excess air is a minimum.

16. Describe the main features of an economiser and explain its advantages and disadvantages.

17. Estimate the percentage gain of heat obtained by employing an economiser, which raises the temperature of the feed water from 92° F. up to 216° F., instead of allowing the feed water to enter the boiler direct at 92° F. Assume the boiler supplies 1150 B.Th.U. to each lb. of feed.

18. An economiser has a heating surface of 1650 sq. ft. and raises the temperature of 17,000 lb. of feed water from 78° F. to 190° F. every hour. Calculate the rate of heat transference per sq. ft. of surface per hour.

19. An economiser receives 16,500 lb. of feed water per hour at 100° F. while the weight of flue gas passed is 35,000 lb. If the flue gases enter the economiser at 690° F. and leave at 350° F., estimate the temperature of the feed water as it leaves the economiser. Assume the mean specific heat of the flue gases is 0·25, and neglect losses.

20. A force pump has a ram 2 in. in diameter and has a stroke of 24 in. Neglecting leakage, how many gallons of water would be forced into the boiler for every 1000 double strokes of the ram. Calculate the force on the ram plunger due to a working pressure in the boiler of 240 lb. per sq. in. gauge.

21. A small marine boiler having a grate area of 36 sq. ft. generates 9090 lb. of dry steam per hour at 215 lb. per sq. in. abs. from feed water at 50° C. Calculate the quantity of coal burned per sq. ft. of grate area per hour if the calorific value of the coal is 8000 C.H.U. per lb. Efficiency of boiler = 78%.

22. A steam wagon using 198 lb. of coal per hour develops 95 H.P. Find the overall thermal efficiency of boiler and engine if the calorific value of the fuel is 8100 C.H.U. per lb.

23. Find the necessary grate area for a boiler supplying steam to a 600 I.H.P. triple expansion engine if the estimated steam consumption is 15 lb. per I.H.P. per hour, the evaporative power of the coal 8 lb. of water per lb. of coal, and the grate can burn 27 lb. of coal per sq. ft. per hour.

24. In a 2 hours' trial for a water tube boiler 4360 lb. of oil of calorific value 19,000 B.Th.U. per lb. were burnt in raising 56,850 lb. of feed water from 46° F. to dry saturated steam at 225 lb. per sq. in. (gauge). Calculate the efficiency of the boiler and the equivalent evaporation per lb. of oil fuel.

25. A 2 hours' trial for a water tube boiler showed that 10,610 lb. of oil fuel, of calorific value 19,000 B.Th.U. per lb., when burnt raised 127,600 lb. of water from feed temp. 70° F. to dry steam at 205 lb. per sq. in. gauge. Calculate the efficiency of the boiler and the equivalent evaporation from 212° F. per lb. of fuel. What is the evaporative power of this boiler ?

26. During a boiler test the average steam pressure was 170 lb. per sq. in. absolute, the dryness fraction of the steam generated 0·97, weight of feed water used per hour 40,000 lb., temp. of feed water 80° C., fuel fired per hour 4400 lb., and the calorific value 7150 C.H.U. per lb. Find the efficiency of the boiler, having given: absolute pressure of steam 170 lb. per sq. in., temp. 186·9° C., sensible heat 189·5 C.H.U. per lb., and total heat 667·9 C.H.U. per lb. (U.L.C.I.)

27. A Lancashire boiler generates 5200 lb. of dry steam per hour at an absolute pressure of 160 lb. per sq. in. The grate area is 34 sq. ft., and 18 lb. of coal are burnt per sq. ft. of grate area per hour. The calorific value of the coal is 7900 C.H.U. per lb., and the temp. of the feed water is 17·5° C. Find the efficiency of the boiler given :

Temp. of steam at 160 lb. per sq. in., 184·2° C.; sensible heat, 186·6 C.H.U. per lb.; total heat, 667·2 C.H.U. per lb. (U.L.C.I.)

28. Describe briefly, with the aid of outline sketches, the chief features of construction of any boiler with which you are familiar, and show the path of the gases from the furnace to the flues. The fittings need not be described. (U.L.C.I.)

29. A Howden high pressure boiler evaporated 16 lb. of water per hour per lb. of oil burnt at a steam pressure of 310 lb. per sq. in. abs. Calculate the efficiency of the boiler if the feed water temperature was 200° F. Calorific value of fuel = 19,000 B.Th.U. per lb.

30. What is meant by *equivalent evaporation from and at 212° F.*?

Find the equivalent evaporation from and at 212° F. for a boiler evaporating 8·5 lb. of water per lb. of coal when working at a pressure of 215 lb. per sq. in. abs. with a feed temperature of 110° F.

31. A boiler evaporates 10 lb. of water per lb. of coal from feed water at 140° F. to steam at 270 lb. per sq. in. abs. and superheated to 467·9° F. Specific heat of steam = 0·6.

Find the equivalent evaporation from and at 212° F. per lb. of fuel.

32. A boiler taking feed water at 135° F. uses 1500 lb. of coal per hour of calorific value 12,500 B.Th.U. per lb. and generates 12,800 lb. of steam per hour at 220 lb. per sq. in. abs. and 0·96 dry. Calculate the efficiency of the boiler and its equivalent evaporation from and at 212° F. per lb. of fuel.

33. As a result of a boiler trial the following results were obtained :

Feed water supplied per hour, 8100 lb. Feed temperature, 86° C.

Boiler pressure, 330 lb. per sq. in. abs. Dryness fraction of steam, 0·97.

Coal burnt per hour, 910 lb. Calorific value of coal, 7,800 C.H.U. per lb.

Find the thermal efficiency of the boiler and the equivalent evaporation from and at 100° C. per lb. of fuel.

34. A steam plant generates 30,000 lb. of steam per hour at 500 lb. per sq. in. abs. with 200 Fahr. degrees of superheat (total heat 1341·9 B.Th.U. per lb.) from feed at 80° F. Estimate the fuel consumption in lb. per hour assuming an overall efficiency of 77% and fuel of calorific value 13,500 B.Th.U. per lb.

35. A radiant heat steam generator using pulverised coal as fuel generated 90,000 lb. of steam per hour at 400 lb. per sq. in. abs. and 200 Fahr. degrees of superheat from feed at 160° F. If the efficiency of the generator was 87·6%, calculate the fuel consumption. Calorific value of fuel 13,500 B.Th.U. per lb. Specific heat of steam 0·618. What is the equivalent evaporation per lb. of fuel from and at 212° F.?

36. A boiler has an efficiency of 72% and the rate of firing is 25 lb. per hour per sq. ft. of grate area. Steam is generated at 400 lb. per sq. in. abs. and 120 Fahr. degrees of superheat from feed at 140° F. Estimate the boiler output in lb. per hour if the calorific value of the fuel used is 13,500 B.Th.U. per lb. and the grate area is 420 sq. ft. Specific heat of superheated steam = 0·648.

37. The combustion chamber of a water tube boiler using pulverised fuel is 19 ft. by 19 ft. by 28 ft., and the heat is released at the rate of 35,000 B.Th.U. per cu. ft. of furnace volume every hour. If the working pressure of the boiler is 500 lb. per sq. in. abs., the steam is given 160 Fahr. degrees of superheat and feed is taken in at 215° F., find the weight of water evaporated per hour if the efficiency of heat transfer is 84%. Specific heat of superheated steam 0·66.

38. A superheater raises the state of 20,000 lb. of saturated steam per hour from 252·4° C. (600 lb. per sq. in. abs.) and 0·97 dry to superheated steam at 452·4° C. and the same pressure. If the specific heat of the steam is 0·619 and the superheater has a surface of 1950 sq. ft., calculate :

(*a*) the heat given to each lb. of steam ;
(*b*) the heat given per hour ;
(*c*) the rate of heat transference per sq. ft. of surface per hour.

39. The following figures were taken from the superheater of a liner.

Temp. of gases into and out of superheater
= 1310° F. and 820° F. respectively.

Temp. of steam into and out of superheater
= 449° F. and 675° F. respectively.

Specific heat of gases and steam = 0·25 and 0·617 respectively.

Calculate the heat given up by the hot gases and gained by the steam per lb. of fuel and the efficiency of the superheater, if 14 lb. of steam are superheated and 18 lb. of air are supplied per lb. of fuel.

40. A separately fired superheater is supplied with steam at a pressure of 310 lb. per sq. in. abs. and dryness fraction 0·9, and raises the

temperature of 40,000 lb. of steam per hour to 395·8° C. If the specific heat of the steam at constant pressure is 0·57, find the thermal efficiency of the superheater if it uses 989 lb. of coal per hour of calorific value 7,800 C.H.U. per lb.

41. Estimate the coal consumption of a locomotive using 9,500 lb. of steam per hour from feed at 80° F. with a boiler pressure of 250 lb. per sq. in. abs. and the steam superheated 60 Fahr. degrees. Take the calorific value of the fuel as 13,000 B.Th.U. per lb., the efficiency of the boiler and superheater as 72%, and the specific heat of superheated steam as 0·61.

42. The following figures were taken from the performance of an air preheater for a steam power plant :

Temperature of air entering preheater	= 60° F.
Temperature of gases entering preheater	= 492° F.
Temperature of gases leaving preheater	= 286° F.
Quantity of air supplied to boiler per lb. of fuel	= 18·8 lb.
Calorific value of coal used	= 14,000 B.Th.U. per lb.

Specific heat of air = 0·24. Specific heat of gases = 0·26.

Assuming no heat losses, find the temperature of the air leaving the heater. What percentage of the calorific value of the coal has been saved ?

43. A boiler plant uses fuel with a chemical composition by weight of carbon 85% and hydrogen 14%. Calculate the minimum air required per lb. of fuel for complete combustion. When 50% excess air at 70° F. is supplied, what is the percentage loss of heat, due to excess air, of the total flue gas loss?

Temperature of flue gases at the entrance to the chimney = 520° F.

Specific heat of flue gases = 0·26. Specific heat of air = 0·24.

44. Find the weight necessary to hold down a dead weight valve for a boiler with a working pressure of 180 lb. per sq. in. abs. The valve opening is $2\frac{1}{2}$ in. in diameter. Also calculate the lift of the valve to give the same area to steam exit from the valve as to steam entrance. What stiffness of spring in the case of a spring loaded valve would be necessary to just permit this lift with the given steam load?

45. With the aid of a line diagram indicate the arrangement and functions of the main components of a pulverised fuel plant.

46. The following figures were taken during the trial of a locomotive boiler lasting 6 hours :

Coal burnt per hour	= 340 lb.
Temperature of air supply	= 60° F.
Grate area	= 12·4. sq. ft.
Ash removed per hour	= 22 lb.
Specific heat of gases	= 0·26.
Specific heat of air	= 0·24.

Minimum air supplied per lb. of coal	= 10·4 lb.
Excess air	= 6·2 lb.
Temperature of flue gases entering chimney	= 570° F.
C.V. of coal	= 13,000 B.Th.U. per lb.

Calculate the percentage of the heat available in the coal which is carried away: (*a*) by the total flue gases, (*b*) by the excess air alone.

47. A Yarrow boiler with a grate area of 65 sq. ft. and a heating surface of 3350 sq. ft. supplied 24,700 lb. of dry steam at a pressure of 300 lb. per sq. in. abs. from feed at 50° F. using 2800 lb. of fuel per hour af calorific value 13,500 B.Th.U. per lb.

Find (*a*) the weight of coal burnt per sq. ft. of grate per hour;
(*b*) the weight of steam generated per lb. of coal;
(*c*) the thermal efficiency of the boiler;
(*d*) the equivalent evaporation per lb. of fuel from and at 212° F.;
(*e*) the ratio of heating surface to grate area.

48. A boiler with economiser taking 8000 lb. of feed water per hour needed a coal consumption of 880 lb. per hour. During an experiment the whole of the flue gases were passed through the economiser and their temperature fell from 700° F. to 420° F. in the process, while the feed water was raised from a temperature of 100° F. to 225° F. Assuming the heat lost by the gases was absorbed by the water, estimate the weight of air supplied to the boiler per lb. of coal. Take the specific heat of the gases as 0·25.

49. The following table shows, for an air temperature of 60° F. and a temperature $t°$ F. inside the chimney stack, the theoretical relation between the height H of the stack in feet and the natural draught d or suction through the boiler, measured in inches of water:

$t°$ F. - - -	300	400	500	600
Relation between H and d - - -	$H = 225d$	$H = 180d$	$H = 156d$	$H = 139d$

Calculate the natural draught for a stack 175 ft. high for each of the stack temperatures given, and by means of a graph find the natural draught for a stack temperature of 350° F. and $H = 175$ ft.

If the actual draught required for the plant were 3 in. of water, due to a superheater, economiser, air preheater and dust extractor in addition to the boiler, what is the minimum draught to be supplied by the fans?

50. Sketch and describe a modern condenser suitable for sea water cooling.

51. State briefly the advantages a condensing engine possesses over a non-condensing one.

52. If an engine discharges dry steam at a pressure of $4\frac{1}{2}$ lb. per sq. in. absolute, determine how many pounds of cooling water at 15° C. must be supplied per min. per pound of steam to a condenser if the final temperature of the cooling water is not to exceed 40° C.

53. $7\frac{1}{2}$ lb. of dry steam at 160° F. and 300 lb. of sea water at 61° F. enter a surface condenser each minute. At what temperature will the condensate leave if the water leaves at 90° F. ? Specific heat of sea water = 0·94. Assume a perfect heat transfer.

54. State the advantages of a surface condenser over a jet condenser.

55. Distinguish between and compare the functions of an air pump, a feed pump, a condensate extraction pump and a circulating pump.

56. What do you understand by the "vacuum" in a condenser, and why is it necessary ? How is the vacuum obtained ?

The vacuum in a condenser is 26·9 in. when the height of the barometer is 29·4 in. What is the absolute pressure in lb. per sq. in. in the condenser, and by how much is the condenser pressure less than the pressure of the atmosphere ? Specific gravity of mercury = 13·6.

(U.L.C.I.)

57. Calculate the condensing surface for a surface condenser with 775 tubes $\frac{3}{4}$ in. external diameter and 10 ft. long and the heat extracted in C.H.U. per sq. ft. of surface per hour if 3800 lb. of steam are condensed per hour and each lb. loses 560 C.H.U.

58. What advantages accrue from employing a regenerative condenser? With the aid of a diagram describe a surface condenser employing the principle of regeneration.

59. The water supplied to a jet condenser has a temperature of 11° C. and an average of 12 lb. is supplied per lb. of steam. The steam has a pressure of 1·05 lb. per sq. in. abs. and dryness fraction of 0·75. Calculate the resulting temperature of the mixture. $h = 71{\cdot}1$ B.Th.U. per lb.; $L = 1032{\cdot}1$ B.Th.U. per lb. for 1·05 lb. per sq. in. abs.

60. Find the diameter of the inlet branch for exhaust steam to a condenser in which the vacuum is 27 in. of mercury. Allow 30,000 lb. of steam per hour and a steam velocity of 300 ft. per second, and determine the volume of the steam for a vacuum of 27 in. by means of graph, using the following values :

Vacuum (in.) - - -	27·14	27·04	26·94	26·73
Vol. of 1 lb. (cu. ft.) - -	242·7	234·8	227·4	214

61. A parallel flow jet condenser condenses 30,000 lb. of steam per hour and maintains a vacuum of 28·16 in. of mercury (0·9 lb. per sq. in. abs.) when supplied with cooling water at 50° F. The difference of temperature between injection water at outlet and steam at inlet is not to be more than 6° F. Calculate the quantity of injection water required in gallons per minute.

If the velocity of the cooling water in the injection pipe is limited to 8·5 ft. per sec., find the necessary diameter of pipe. Temperature of

steam at 0·9 lb. per sq. in. = 98 2° F., sensible heat 66 B.Th.U. per lb. and total heat = 1100 8 B.Th.U. per lb.

62. A condenser condenses 42,000 lb. of steam per hour with cooling water, at 48° F., entering the condenser at the rate of 3000 gallons per minute. The steam loses 1000 B.Th.U. per lb. and suffers a temperature drop of 10 F. in the process of condensation. Estimate the vacuum in the condenser.

63. It is required to fit an air pump to a condenser to remove an estimated maximum of 48 lb. of air per hour. The vacuum and temperature at the point of pump suction are respectively 28 37 in. of mercury and 30 94° C. Calculate the volume of air to be removed in cu ft. per min. Vacuum corresponding to 30 94° C. is 28 67 in. of mercury, $R = 53\ 2$ ft. lb. per lb per Fahr. degree for air. 1 in. of mercury corresponds to 0 491 lb. per sq. in. Barometer reading = 30 inches, equivalent to 14 7 lb. per sq. in.

CHAPTER IV

EXTERNAL COMBUSTION ENGINES—KINDS OF STEAM PRIME MOVER—FUNCTIONS OF PARTS—ENGINE OPERATION—PERFORMANCE AND TESTING

Simple steam reciprocating engine. The main parts of a simple non-condensing engine and their functions are shown in the figure and in the chart below.

Main Parts	Explanation
1. Cylinder. CY.	This receives the steam and acts as container for the piston. Some of the heat energy of the steam is converted into kinetic energy or mechanical work by giving linear motion to the piston.
2. Piston. P.	Maintains an almost steam-tight sliding joint in the cylinder, and moves under the action of the steam pressure. Steel or cast iron rings are fitted into grooves in the piston and make a joint with the cylinder walls.

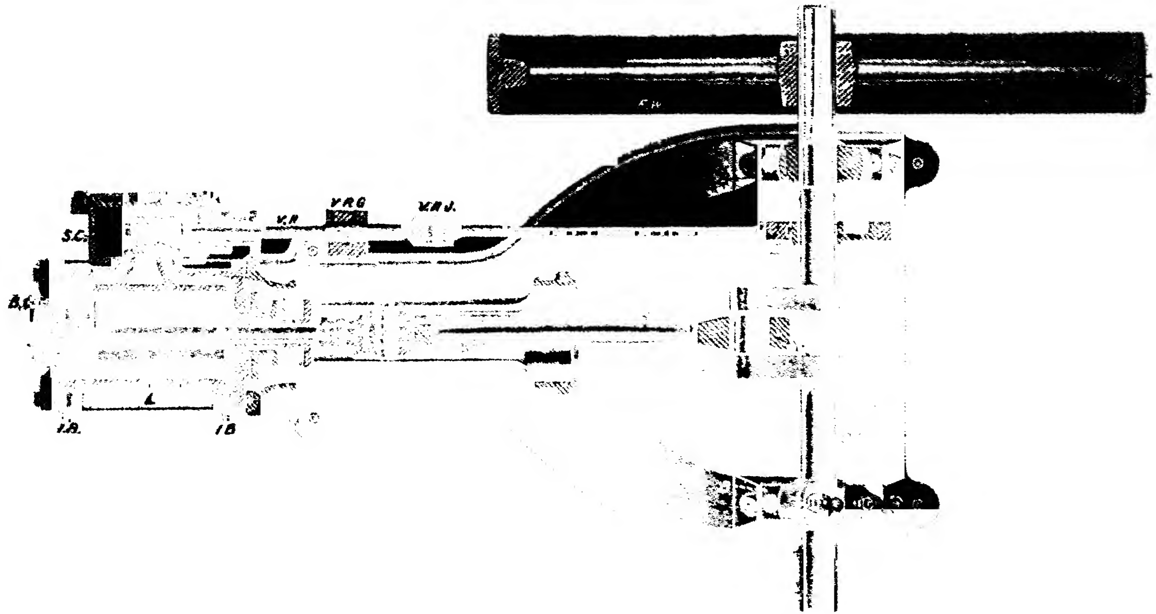


FIG. 54 Single cylinder reciprocating engine.

Main Parts	Explanation
3. Piston rod. P.R.	This connects the piston to the crosshead and transmits the load on the piston. It acts as a tie and a strut alternately, according to the backward and forward motion of the piston.
4. Gland and stuffing box. S.B.	Prevents steam escaping between the piston rod and the cylinder, also between the valve rod and steam chest.
5. Crosshead and gudgeon pin. C.H. and G.	Forms a junction between the piston and connecting rods, the load being transmitted through the gudgeon pin while the crosshead slides along its guides.
6. Connecting rod. C.R.	By an oscillating motion converts the translational motion of the crosshead to the rotary motion of the crank pin. Acts as both a tie and a strut, pulling and pushing alternately.
7. Crank pin. C.P.	Receives the thrust and pull of the connecting rod, and being connected to the crank it exerts a torque or turning moment on the crank shaft.
8. Crank. C.	Transmits the torque from the crank pin to the crank shaft, which rotates in the crank shaft bearings.
9. Crank shaft. C.S.	Transmits its rotary motion to the machinery, through power pulleys, belt or rope drive or toothed wheel transmission.
10. Eccentric. E.	Is driven by the crank shaft and controls the motion of the slide valve, through the valve rod.

Main Parts	Explanation
11. Slide or other valve. S.V.	Controls the admission and exhaust of steam to and from the cylinder. Also controls the quantity of steam. Slides to and fro on the steam chest face.
12. Governor.	Controls the engine speed within limits by regulating either steam supply or its pressure. Prevents racing or slowing up as the load on the engine varies.
13. Flywheel. F.W.	Equalises the energy of the engine during each revolution, and carries it past the **dead points** when the crank and connecting rod are in the same straight line. Prevents jerky motion and thus reduces fluctuations of speed per revolution. Is keyed to the crank shaft.
14. Engine frame or sole plate. B.P.	Takes the reactions of the mechanism and affords means of support and connection between the component parts of the engine.

The engine is called **double acting** because steam is admitted first to one side of the piston and then to the other.

The details mentioned vary considerable in different engines. Marine and locomotive engines possess no flywheel or governor, because in each case the engine drives a huge mass, and there is plenty of time to regulate the engine by hand to suit the speed and load. Marine engines often have a governor, which comes into action before dangerously high speeds can be reached.

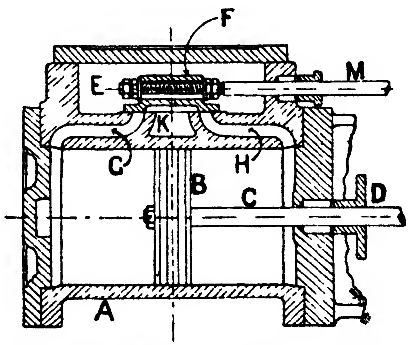
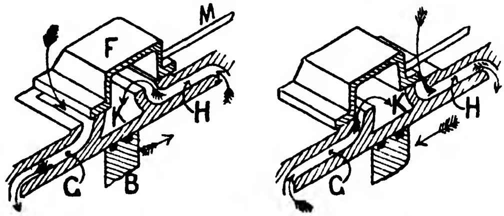


FIG. 55. Sectional view steam engine cylinder.

Fig. 55 shows the cross-section of the cylinder of a simple steam engine. Steam passes through the steam chest and enters the cylinder

when the D slide valve F opens the left-hand port G. The piston is pushed forward to the right and the crank rotated. Then at the end of its stroke steam is directed through H to the right-hand side of the piston and the latter is pushed towards the left, and at the same time steam is forced out on the other side through the



(a) (b)

FIG. 56. Distribution of steam by slide valve.

port G to the exhaust port K and then to the atmosphere. The exhaust steam pressure is called the back pressure on the piston. Figs 56 (a) and (b) show how the valve controls the flow of steam

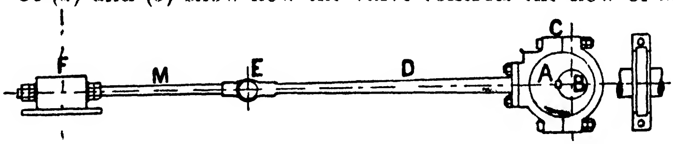


FIG. 57 Arrangement of eccentric and rods for driving slide valve.

into the cylinder. The valve is usually designed to admit steam only during the early part of the stroke. It then cuts off the supply and allows the steam to expand, and so economises steam and fuel. To drive the valve an eccentric is often employed, as it acts as a small crank on the crank shaft and gives the small travel necessary to the valve. B is the centre of the crank shaft (Fig. 57), while A is the centre of the eccentric sheave, which is keyed and thus fixed to the shaft. The strap C is free to turn on the sheave, which rotates and gives the valve a stroke equal to twice AB. Fig. 58 shows the piston for a small engine. Both piston and rings

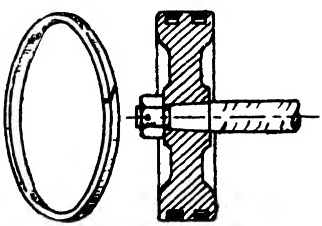


FIG. 58. Piston and ring.

are made of cast iron. Large pistons have to be made conical, or box-shaped and ribbed, to withstand the large pressures, and the materials used are forged or cast steel. The rings, which are sprung into position and the slots staggered, serve to lessen the leakage of steam past the piston. Fig. 59 shows a simple stuffing box and gland. Set screws D tighten the gland C on to the asbestos packing B. The more efficient metallic packing used on large modern engines offers much less frictional resistance and allows less leakage.

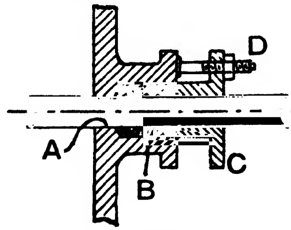


FIG. 59. Stuffing box and gland for rendering piston steam tight.

In Fig. 60 the brass bearing blocks B lessen the friction between the crosshead gudgeon pin and the small end of the connecting rod. These brasses are made in halves, and in such a way that when the steel bolts and cap C are in position and tightened they cannot move

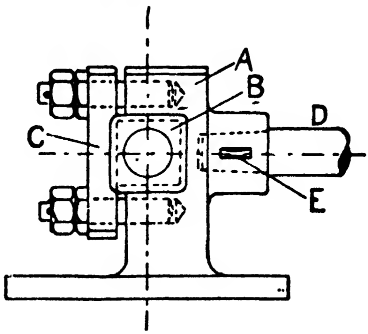


FIG. 60. Side elevation of a crosshead.

in any direction relative to A. Check nuts and split pins prevent any loosening of the nuts, and provide an efficient fastening in a case where too much tightening of the nuts would cause the brasses and the gudgeon pin to seize and prevent rotation. The main part A of the crosshead is provided with a flange sliding between guides which are not shown. Adjustment for wear of the brasses is made easy by the insertion of flat liners between the two portions.

If the bolts are just slackened these liners can be removed and ground down to the correct thickness. The small connecting rod shown in Fig. 61 is forked at its small end A to take the gudgeon

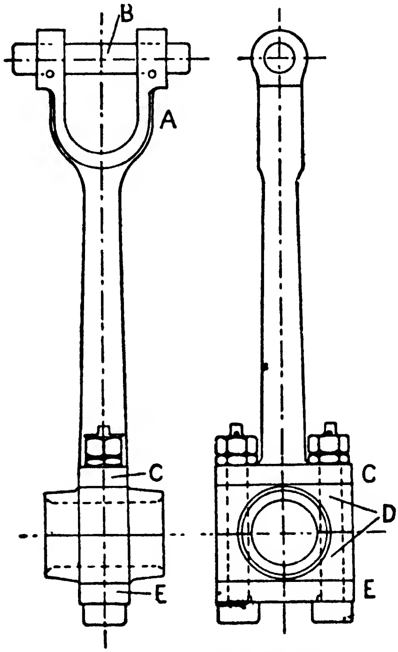


FIG. 61. Connecting rod.

pin B. The rod tapers towards the big end and is palmed at C. Two steel bolts pass through the brasses and connect the cap E to

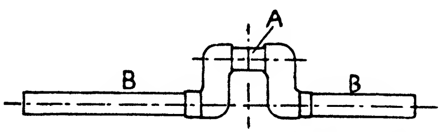


FIG. 62. A bent form of crank shaft.

C. The bearing blocks D are often made of bronze and lined with white or bearing metal to lessen friction. Fig. 62 shows a small

bent-up crank shaft, and Fig. 63 a sectional elevation of the main bearings. D forms a small oil reservoir for lubricating the bearing, in which bearing blocks are made similarly to those already described.

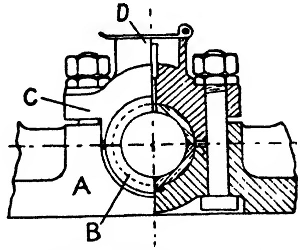


FIG. 63. Sectional elevation of a main bearing.

A large flywheel is necessary if the jerky motion of the engine is to be reduced to a minimum. It forms a reservoir for energy by regulating the inward flow of energy from the engine and the outward flow to the machines. However, it cannot alter the total amount of energy stored or prevent a gradual steady increase, or decrease, of speed, so that a governor has to be employed. The latter keeps the engine at a steady mean speed by regulating the supply or pressure of steam to the cylinder Fig. 64 shows a diagrammatic arrangement for achieving control over the steam supply. The governor alters the position of the throttle valve C, so as to obstruct the flow of steam when speed is increasing and to widen the passage when speed slackens. The engine speed is communicated to the shaft H from the pulley K through bevel wheels L. The higher the speed the greater will be the tendency for the heavy balls F to fly outwards and raise the dead load P and sleeve N. This causes the bell crank lever Q to pull S inwards and start closing the valve C about its fulcrum D. A slowing of the engine speed will cause motion in the reverse direction, tending to open the valve. The load P steadies the action of the governor and gives it a wider range of action.

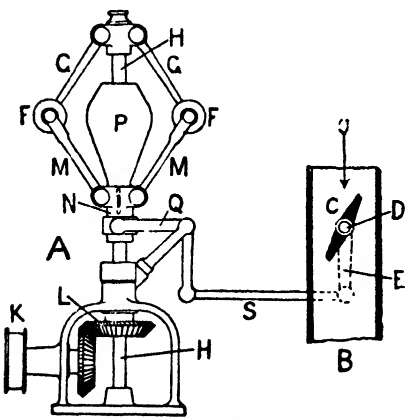


FIG. 64. Diagram showing how the governor controls the steam supply.

Lubrication of the piston and crosshead is often carried out by a drip feed arrangement, the rate of dripping being controlled by a needle valve. The main bearings are often lubricated by ring oilers —metal rings dipping into oil wells and lifting oil to the shaft as the latter drags them slowly round. The crank pin is often bored, and oil from a sight feed lubricator fed to the centre of the pin, whence it is thrown outwards to the bearing by centrifugal force.

The efficiency of the engine just described is not very high, probably not more than 10%. In modern plants the efficiency is increased by employing (*a*) a condenser so as to allow for expansion of the steam below atmospheric pressure and reduce back pressure, (*b*) metallic packing in stuffing boxes to lessen friction, (*c*) forced lubrication to all bearings by means of pumps, (*d*) improved valves and valve gears, (*e*) more sensitive governors, (*f*) means of lessening condensation in the cylinders, (*g*) the use of superheated steam, (*h*) lagging for pipes and cylinders to prevent radiation losses, (*i*) improved workmanship and better materials, giving lightness and greater efficiency in boiler, engine and condenser. As an alternative to (*a*), if the steam is not fully expanded in the main engine it can be used as process steam in dye-works, laundries, or used to run back pressure engines or low pressure turbines, or for preheating both feed water and air to the boilers.

Construction for determining the position of the piston. The following construction will give the position of the piston for any crank angle. With centre C (Fig. 65) representing the crank shaft centre, describe a circle with radius r to represent the path of the crank pin. Draw RL as a diameter and produce it to represent the line of the stroke of the piston. Make the angle BCL to correspond with the position of the crank for which the position of the piston is required. With centre B and radius equal to the length of the connecting rod, describe an arc cutting the line of stroke at A. Then A gives the position of the crosshead pin for the crank position CB. If DL and ER are made equal to AB, then D and E mark the limits of travel of the crosshead pin, and thus also represent the limits of travel of the piston itself, since the crosshead and piston are rigidly connected. When the crank passes through the positions CL and CR it is said to be on the dead points, L being called the **inner dead**

point or **centre,** and R the **outer dead point or centre.** With centre A and radius AB describe an arc cutting LR at P. Then, because DL and AP are both equal to AB, LP is equal to DA. Thus LP represents the forward travel of the piston from the inner dead centre when the crank is in the position CB.

It should be noticed that the greater the ratio of connecting rod length AB to crank length BC, the more nearly does the arc BP

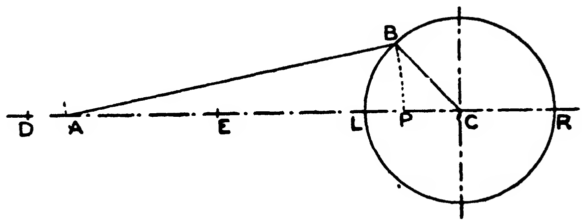


FIG. 65. Construction for finding the piston position.

approximate in position to the perpendicular from B on to LR. In fact, in practice, the perpendicular is often drawn in place of the arc for the sake of simplicity. The construction just described will be used later when dealing with valve diagrams.

Turning moment on the crank shaft. For any position of the piston the forces acting on it are transmitted through the piston

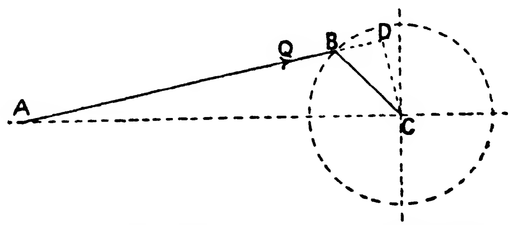


FIG. 66. Measurement of the turning moment.

rod and crosshead to the connecting rod, and so a push or pull is exerted on the crank pin. The forces acting on the crank pin tend to rotate the crank shaft; this tendency is called the **turning moment,** and its magnitude is given by the product of the magnitude of the force Q (Fig. 66) acting at that instant along the con-

necting rod and the perpendicular distance CD from C on to the line AB produced.

By finding the turning moment on the crank for various angular positions, diagrams can be constructed, and these **turning moment diagrams,** as they are called, are used for determining the size of flywheel necessary for the engine, since the flywheel is to balance the effort during a revolution.

Example. *Find the turning moment on the crank if the force acting along the connecting rod is* 18,000 *lb. and the perpendicular distance of the crank shaft centre on to the connecting rod is* 23 *in.*

$$\text{Turning moment} = \frac{18{,}000 \times 23}{12} \text{ or } \mathbf{34{,}500 \text{ lb. ft.}}$$

The forces acting on the crosshead pin consist of (1) the piston load transmitted along the piston rod, (2) the force acting along the connecting rod, and (3) the reaction of the guides on the crosshead. If friction is neglected, the latter force acts normally to the guides. When the piston load is known for any given position, the magnitude of the other forces may be determined by employing the principle of the triangle of forces.

The crank and connecting rod mechanism is of fundamental importance to the engineer, and the following experiment should be carefully performed and the results obtained studied. The high speeds of modern reciprocating engines demand high piston accelerations, and consequently large forces to produce them. Every endeavour is made to make the reciprocating parts light and strong, since the force necessary to accelerate the parts varies jointly as the mass of the parts and their acceleration. For this reason engine designers give great attention to the selection of materials which offer a large resistance to the forces set up in them, and thus reduce the weight of the reciprocating parts to a minimum consistent with safety.

EXPT. 32. **Crank and connecting rod mechanism.**

OBJECTS. (*a*) *To investigate the relative piston displacement with crank movement.*

(*b*) *To compare the piston velocities during one crank revolution.*

(*c*) *To compare the piston accelerations during one crank revolution.*

Apparatus. A wooden board secured to a vertical wall with a rotating crank, connecting rod and piston mechanism mounted on the board. The piston guides are graduated in inches for the stroke length, and the crank pin circle is graduated at 30° intervals (Fig. 67).

Method of procedure. Set the crank at its inner dead centre position O on Fig. 67, when the arrow on the model piston should be opposite O on the guide scale. Give the crank a rotation of 30°, and note the piston displacement by the position of the arrow relative to the guide scale. Repeat the experiment for each 30° of

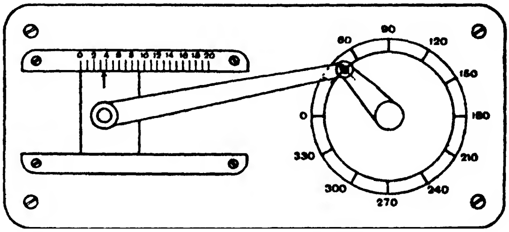


Fig. 67. Engine mechanism.

crank rotation and tabulate the results. Now if the crank pin rotates at a uniform speed, each 30° will be covered in the same time, so that the mean velocity of the piston will be proportional to the $\dfrac{\text{displacement}}{\text{time for }30^\circ\text{ rotation}} = \dfrac{\text{displacement}}{1}$ where the time required to rotate the crank 30° is regarded as the unit of time, thus the mean velocity is proportional to the difference between the two consecutive displacement readings for each 30° of crank rotation. These should be assigned positive or negative values, according to whether the displacement is increasing or decreasing. Since acceleration is the rate of change of velocity, the mean piston acceleration may be determined by the difference of two consecutive velocity readings for 30° of crank rotation. Graphs can then be drawn of piston displacement, piston velocity and piston acceleration against crank rotation (Fig. 68).

Note. In determining the acceleration due regard must be given to the sign of the velocity, for example, the mean velocity between 330 and 360° is $-1{\cdot}75$ and between 0 and 30° is $+1{\cdot}75$, so that the change of velocity is $1{\cdot}75 - -1{\cdot}75$ or $+3{\cdot}5$.

OBSERVATIONS AND DERIVED RESULTS.

Crank Angle in Degrees	0	30	60	90	120	150	180	210	240	270	300	330	360
Piston Displacement in Inches	0	1·75	6·0	11·5	16·0	18·8	20	18·8	16·0	11·5	6·0	1·7[illegible]	0
Mean Velocity of Piston	+1·75	+4·25	+5·5	+4·5	+3·1	+1·2	−1·2	−3·1	−4·5	−5·5	−4·25	−1·75	
Mean Acceleration of Piston	+3·5	+2·5	+1·25	−1·0	−1·4	−2·2	−2·4	−2·2	−1·4	−1·0	+1·25	2·[illegible]	[illegible]

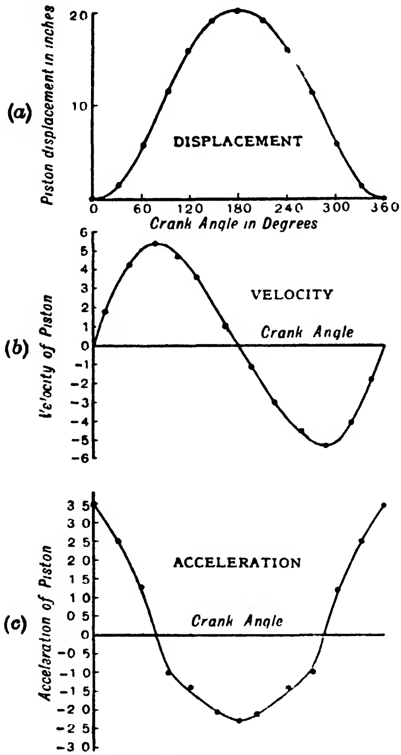


FIG. 68. Expt. 32.

GRAPHS AND CONCLUSIONS

(*a*) The piston displacement increases with the crank angle up to the outer dead centre, and then decreases until the inner dead centre is reached, with approximately simple harmonic motion.

(*b*) The piston velocity increases to mid-stroke, falls to zero at the ends of stroke, and assumes a negative value on the return stroke.

(*c*) The piston acceleration is a maximum at the inner dead centre where the velocity is changing from positive to negative, is zero towards the middle of each stroke, and attains a supplementary but lesser maximum at the outer dead centre

Ratio of expansion. This is given by the fraction

$$\frac{\text{clearance volume} + \text{stroke volume}}{\text{volume up to point of cut-off}}.$$

The clearance volume is the volume at the cylinder end not

swept by the piston. This is necessary for mechanical reasons, to keep steam to act as a cushion in bringing the piston to rest without shock at the end of each stroke. If the exhaust valve is shut before the end of the exhaust stroke, the piston compresses the trapped steam and raises its temperature. In this way the steam about to enter the cylinder for the next stroke is not cooled and condensed to the same extent by coming into contact with cold parts. Clearance is usually small, but its effect is to raise the expansion curve, which compensates somewhat for the work done in compression.

The hypothetical diagram. The theoretical diagram ABCDE in Fig. 69 of the work done in a steam engine cylinder with hyperbolic expansion has been mentioned in Chap. II. This diagram is generally referred to as the hypothetical diagram when (*a*) the clearance volume is neglected, (*b*) the valves act instantaneously in opening and closing, and (*c*) the steam, during admission and during exhaust, remains at constant pressure. The mean pressure is calculated by the formula :

$$p_m = p_i\left(\frac{1+\log_e r}{r}\right) - p_b,$$

where p_i = absolute pressure of the steam supply in lb. per sq. in.

r = ratio of expansion,

$\log_e r$ = hyperbolic or Napierian logarithm of r,

p_b = absolute back pressure on the piston throughout the stroke,

p_m = the mean effective pressure (M.E.P.) difference on the piston in lb. per sq. in.

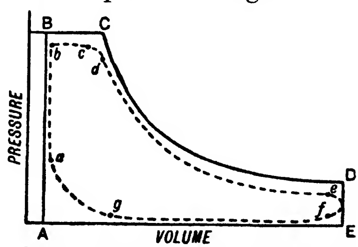


FIG. 69. Hypothetical and probable indicator diagrams.

The actual M.E.P. is always less than the value calculated by means of this formula. The probable diagram in practice is shown by the dotted lines *abcdefg* (Fig. 69), and the ratio

$$\frac{\text{actual diagram area}}{\text{area of hypothetical diagram}},$$

is called the **diagram factor.**

Providing the hypothetical and actual indicator diagrams are drawn to the same pressure and volume scales and both diagrams are based on the same cylinder dimensions, the diagram factor already defined may be replaced by the equivalent ratio :

$$\frac{\text{Probable or actual mean effective pressure}}{\text{Hypothetical mean effective pressure}}.$$

The expression

Probable or actual mean effective pressure = Diagram factor multiplied by hypothetical mean effective pressure

is in a very convenient form for dealing with problems on cylinder design.

Napierian logarithms. In this section of the work on heat engines the natural or Napierian logarithm is used, and the logarithm of a number is taken to the base e, where e is 2·7183 approximately, instead of, as in common logarithms, to a base of 10. In order to obtain the Napierian logarithm of a number, the logarithm of the number to the base 10, or the common logarithm, is multiplied by 2·3026.

Example 1. *Find the logarithm of 3 to the base e, i e. $\log_e 3$.*

$$\log_e 3 = 2{\cdot}3026 \times \log_{10} 3 = 2{\cdot}3026 \times 0{\cdot}4771 = 1{\cdot}0986.$$

Example 2. *In a steam engine cylinder the initial pressure is 90 lb. per sq. in. absolute, and the cut-off is at $\frac{3}{8}$ stroke. Estimate the M.E.P., assuming a back pressure of 15 lb. per sq. in. absolute.*

Here $r = \frac{8}{3}$, $p_i = 90$ lb. per sq. in., $p_b = 15$ lb. per sq. in., $\log_e r = 0{\cdot}9806$.

Therefore $p_m = 90\left(\dfrac{1 + 0{\cdot}9806}{2\frac{2}{3}}\right) - 15 = 51{\cdot}8$ lb. per sq. in.

This result could also be obtained by drawing and measurement.

On the pressure axis (Fig. 70) mark off OA and OB to represent 15 lb. per sq. in. and 90 lb. per sq. in. respectively, and mark off 8 units on the volume axis to represent the stroke volume. C indicates the point of cut-off if BC represents three-eighths of the stroke volume AE. To draw the expansion curve CD, which is assumed to be a hyperbola, choose a number of points p, q, r and s in BC produced and join them to O. These radial lines cut the perpendicular CF through C in the points

a, *b*, *c* and *d* respectively. Then by completing the rectangles C*awp*, C*bxq*, C*cyr* and C*d*D*s*, the points *w*, *x*, *y* and D on the expansion curve are obtained. Draw a smooth curve through the points C, *w*, *x*, *y* and D to complete the expansion curve. The hypothetical diagram ABCDE is completed by the lines DE and EA, and this area represents the useful work done in the cylinder during one stroke, while OPEA represents the work done in overcoming the back pressure on the piston.

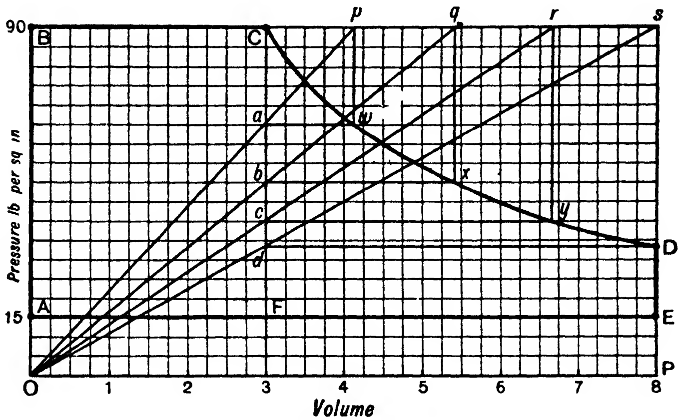


FIG. 70. Construction of a rectangular hyperbola.

Now determine the area of the figure ABCDE either by means of a planimeter, by counting squares, by employing the mid-ordinate rule or by Simpson's rule.

If a planimeter is employed the result could be obtained as follows:

Area by planimeter 1st reading − 2nd reading

$= (64{\cdot}07 - 60{\cdot}74)$ sq. in.

3·33 sq. in.

Length of base 3·2 in.

$$\therefore \text{ Average height of diagram} = \frac{\text{area of diagram}}{\text{length of base}}$$

$$= \frac{3{\cdot}33 \text{ sq. in.}}{3{\cdot}2 \text{ in.}} = 1{\cdot}0406 \text{ in.}$$

On the pressure scale 1 in. represents 50 lb. per sq. in.

$\therefore$ 1·0406 in. represents $1{\cdot}0406 \times 50$ or **52 lb. per sq. in.**

Example 3. *The diameter of a steam engine cylinder is 6 in. and the stroke 10 in. If the initial pressure of the steam entering the cylinder is 220 lb. per sq. in. abs. and the back pressure is 3 lb. per sq. in. abs., find the mean effective pressure. Neglect clearance and take the cut-off at ¼ stroke. Taking a diagram factor of 0·7, estimate the actual mean effective pressure.*

$$p_m = p_i\left(\frac{1+\log_e r}{r}\right) - p_b$$

$$= 220\left(\frac{1+1\cdot3863}{4}\right) - 3$$

$$= 131\cdot25 - 3 = 128\cdot25.$$

Ans. **128·25 lb. per sq. in.**

$p_i = 220$ lb. per sq. in.

$r = 4.$

$p_b = 3$ lb. per sq. in.

$\log_{10} r = 0\cdot6021.$

$\log_e r = 0\cdot6021 \times 2\cdot3026 = 1\cdot3863.$

If the diagram factor is 0·7, actual mean effective pressure = 0·7 × 128·25 or **89·8 lb. per sq. in.**

Admission. It is usual to admit steam to the cylinder a little before the piston gets to the end of the exhaust stroke, so as to have plenty of steam available on the forward stroke. On the diagram (Fig. 69) this would produce the inclined line *ab* instead of the vertical line. The **lead** of a slide valve is the width of steam port uncovered for the admission of steam at the commencement of either stroke of the piston; *i.e.* it is the amount by which the valve "leads" or opens the steam port before the piston starts to move from a dead point. To obtain the lead the eccentric must have moved the valve a distance equal to the outside lap plus lead from the mid-position shown in Fig. 71. The **steam or outside lap** is the name given to the length *l* at each end of the valve where it protrudes beyond the steam ports S_1 and S_2. When the valve is in the position shown, the eccentric should also be in its mean position and ready to move the valve to its extreme position in either direction.

FIG. 71. Outside lap.

Suppose the eccentric's position is represented by OU in Fig. 72, where LR represents the **travel** of the valve, or twice the throw of the eccentric. To supply lead to the valve the eccentric must have moved through an angle α to OE_1, where OM is the steam lap, MN the

lead and E_1N a perpendicular on to OC_1. This will be fairly representative of the actual facts, because the eccentric rod is long and its inclination to the line of stroke can be neglected. In other words, the travel of the valve is assumed to be the same as the horizontal movement of the eye or centre of the eccentric sheave. OC_1 represents the position of the crank at the commencement of a piston stroke. Thus the **angle of advance** of the eccentric is the angle by which it is in advance of the crank minus one right angle; for example, if the eccentric is 120° in advance of the crank the angle of advance will be $120° - 90°$ or 30°. The crank and eccentric will always be separated by the angle C_1OE_1. As the piston moves forward and gathers speed the steam supply is restricted by pipes, passages and valves and cannot quite keep up with the piston, and there is a *throttling* of the steam, that is, a gradual drop of pressure with practically no work being done. This is shown by the dotted line *bc* (Fig 69).

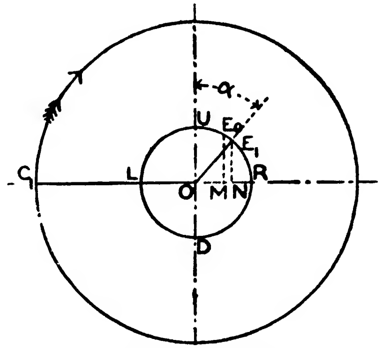


FIG. 72. Setting of an eccentric for a slide valve having lap and lead.

(. **Cut-off and expansion.** This occurs when the valve, moving this time to the left, is in the position shown in Fig. 73. The left steam port S_1 has just been closed, and the greater the outside lap the earlier will closing occur in the piston stroke. It can be easily seen that the advance given to the eccentric also means an earlier return of the valve and an earlier cut off of steam supply. Thus both outside or steam lap and giving advance to the eccentric are necessary for expansive working. Earlier cut-off can also be effected by decreasing the travel of the valve without altering the lead. As the valve closes, the steam has to pass through a rapidly diminishing opening, and a rapid drop in pressure is caused. The steam is said to be *wire drawn*, and the

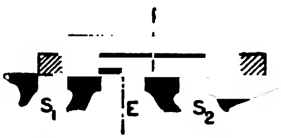


FIG. 73. Lap in a slide valve for expansive working.

effect produces the rounded dotted curve *cd* (Fig. 69). Wire-drawing is more noticeable for high ratios of expansion.

The expansion curve which steam follows in the engine cylinder varies according to the type of engine and running conditions. Its equation is probably something like $pv^{1\cdot135}=\text{const.}$, which is not strictly either isothermal or adiabatic, but an expansion which is between isothermal and adiabatic.

Exhaust and cushioning. To reduce the back pressure and allow of a quick discharge of steam the exhaust valve is arranged to open

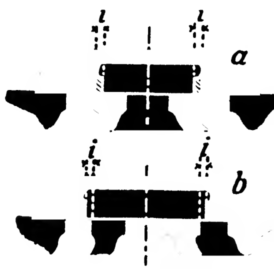


FIG. 74. (*a*) Valve having positive inside lap.
(*b*) Valve having negative inside lap.

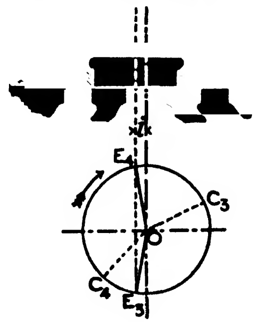


FIG. 75. Setting of the eccentric for a valve having positive inside lap.

a little before the end of the stroke. This effect is shown at the toe of the diagram (Fig. 69) by the rounded end *ef*, where the release is shown by the rapid drop in pressure to exhaust. **Exhaust or inside lap** controls the timing of the opening of the exhaust valve to the release of steam. Positive and negative inside lap are shown in Fig. 74. Fig. 75 shows the valve with positive lap moving to the right and about to close the left-hand port to the exhaust. The position of the eccentric must be OE_3 for opening and OE_4 for closing. This gives the corresponding positions OC_3 and OC_4 for the engine crank. The crank position OC_3 shows that the exhaust valve is opened before the end of the stroke. OC_4 marks the crank position when the exhaust closes and the steam in the cylinder is compressed and cushioned. Positive inside lap produces later release and earlier cushioning. In Fig. 69 point *e* marks the opening

of the exhaust valve and g the closing while the portion ga represents cushioning. The latter operation completes the cycle. When the inside lap is negative, E_3 and E_4 fall on the opposite side of the vertical through the centre by the same amount i. This means that opening to exhaust, or release, occurs earlier and cushioning later. The foregoing facts are best studied and verified by employing a model of the valve mechanism.

Summary of results. The positions of the eccentric centre E_0, E_1, etc., relative to the crank shaft centre O for the commencement and completion of the major operations in the simple reciprocating steam engine are shown in Fig. 76 for a slide valve with no inside lap. In this diagram the eccentric circle may be drawn full size, and the same circle can represent the crank pin circle to some scale. Thus the point C_0 represents the position of the crank pin when the eccentric centre is at E_0, and similarly for the other points. E_1OE_4 is the angle of advance. If OM is the outside lap l, then a perpendicular through M will mark the points E_0 and E_2, which are the positions of the eccentric centre for admission and cut-off respectively. Also, if the angles E_0OC_0 and E_2OC_2 are made equal to the angle E_1OC_1, then C_0 and C_2 will mark the corresponding positions of the crank pin at admission and cut-off. This should be readily understood as the distance OM measures the travel of the valve from its mid-position, when the left-hand port is about to open to steam and the valve is moving to the left, or about to close to steam when the valve is moving to the right. In Fig. 77 the positions of the valve at admission, dead point and cut-off are shown at 0, 1 and 2.

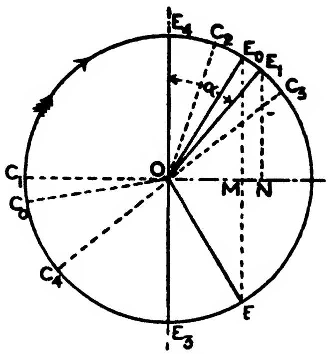


FIG. 76. Events for left-hand side of piston.

With no inside lap the valve begins to release steam from the left-hand side of the piston directly it moves from its mid-position towards the left. Hence the eccentric centre will be at E_3 (Fig. 76) and the crank at C_3. At cushioning, or the com-

mencement of compression and the closing of the port S_1 to the exhaust of steam, the valve will have returned to its mid-position, but now travelling to the right, and the positions of the eccentric centre and crank pin centre will be at E_4 and C_4 respectively. The angles E_3OC_3 and E_4OC_4 are made equal to E_1OC_1 as before. The valve positions at release of steam to exhaust and at cushioning are shown at 3 and 4 in Fig. 77.

The corresponding diagram showing the eccentric and crank pin centres at admission, cut-off, release, and cushioning for the right-

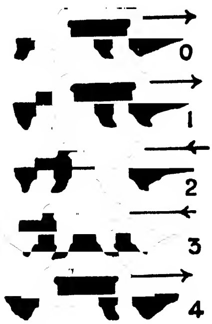


FIG. 77. Valve positions for events of the left-hand side of the piston.

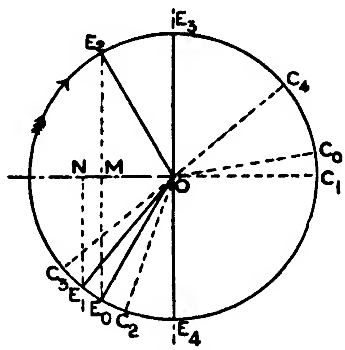


FIG. 78. Events for the right-hand side of the piston.

hand steam port and the right-hand side of the piston are shown in Fig. 78.

It is important that the student should study the above results in conjunction with an experiment on a model of a slide valve and steam engine mechanism, noting carefully the eccentric and crank positions for steam action and exhaust action on both sides of the piston.

EXPT. 33. **A simple slide valve.**

OBJECTS. (*a*) *To show the effects of angle of advance and lead.*

(*b*) *To show the effects of outside and inside lap upon the steam distribution.*

APPARATUS. The apparatus for this experiment consists of a wooden model of a steam engine mechanism with a crank connect-

ing rod, piston, piston rod, cylinder, steam chest and a "*D*" slide valve (Fig. 79). The eccentric is made so that, by means of a dog clutch and thumb screw, it can be rotated and clamped with varying angles of advance. Pieces of wood, with dowels, are made which can be fitted to the slide valve to form outside and inside lap.

METHOD OF PROCEDURE. Arrange the eccentric so that it is 90° in advance of the crank when this is at the inner dead centre. In this position the slide valve is in mid-position and the piston is at the end of its stroke ; thus there is no admission of steam to drive the piston on its return stroke or to cushion its forward stroke. Next move the eccentric so that it is about 120° in advance of the

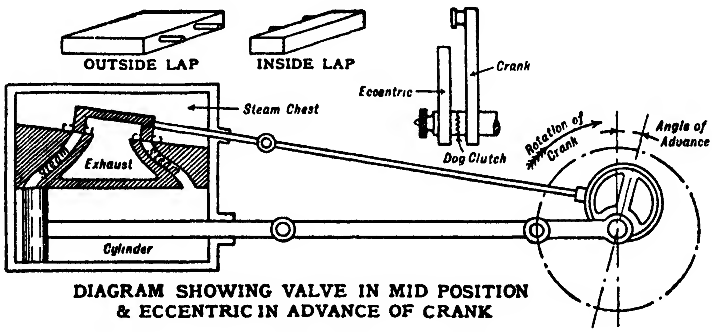


FIG. 79. Model of simple slide valve.

crank, and notice that the steam port is open, and has admitted steam before the piston reached the end of its stroke. This opening to steam is known as the lead of the valve, and is the amount of steam port open when the piston is at the end of its stroke. Vary the angle of advance and note its effect on the lead. Attach to the valve on each end the strips to produce outside lap and arrange the angle of advance accordingly ; carefully revolve the crank, and notice the effect of this outside lap on each side of the piston. Now add the strips for inside lap and again revolve the crank. Notice the effect of inside lap, particularly its connection with exhaust. Draw a circle 4 in. in diameter and carefully mark, in the form of radii, the crank position at admission, cut-off, release and compression respectively. Draw four diagrams to show the relative position of the valve with the ports on the valve face for each of the four events. Compare these positions with the corresponding positions when the eccentric is set with no angle of advance.

CONCLUSIONS. From the experiment write out the following conclusions :

(1) The effect of angle of advance and lead.

(2) The effects of outside lap on steam admission and exhaust on both sides of the piston.

(3) The effects of inside lap on steam admission and exhaust on both sides of the piston.

(4) From the experiments carried out with the valve to determine the four events, construct an approximate indicator diagram for this model engine.

Reversal of rotation of the engine. Referring to Fig. 76, it should be noticed that if the eccentric were keyed in the position OE_1, when the corresponding position of the crank is OC_1, then the rotation of the crank is clockwise as shown in the diagram. If, however, the eccentric were keyed in a position symmetrically opposite to OE_1 (*i.e.* near the position marked OE_2) while the relative crank position is at OC_1, then the crank would be given anticlockwise rotation. This is because, for the two symmetrical positions of the eccentric just specified, the valve would be in the same position relative to the cylinder ports but would be caused to move to the right for one position of the eccentric and to the left for the other. Thus *to reverse an engine with an eccentric operated slide valve, the centre line of the eccentric must be moved over to a symmetrically opposite position when the crank is at one of the dead centres.*

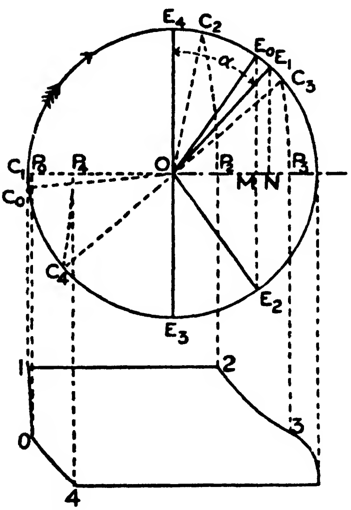


FIG. 80. Construction for determining the probable indicator diagram for a given slide valve.

Probable indicator diagram. Using the construction for determining the piston position for various crank angles already given on p. 167, it will be found that P_0, P_1, P_2, P_3 (Fig. 80) will mark the relative positions of the piston if O is regarded as the mid-position.

By projection from P_0, P_1, P_2, P_3 the probable indicator diagram 0, 1, 2, 3, 4 may be constructed, 2, 3 marking the expansion curve and 4, 0 the compression curve. (See Expt. 33.)

Eccentric and crank positions for a valve with inside lap. Fig. 81 shows how exhaust lap equal to OT affects the position of the eccentric centre at release (E_3) and cushioning (E_4). By rotating all the lines excepting OC_1 anticlockwise through $90° + \alpha$, then the points E_4, E_0, etc., will fall upon corresponding crank positions when the difference in scale due to the difference in the throw of the eccentric and the length of the crank is considered. This is shown

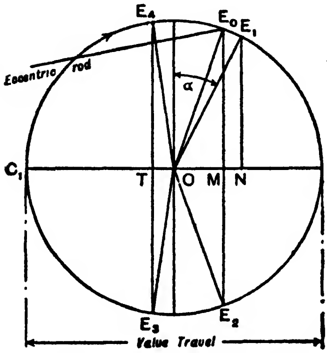


FIG. 81. Valve diagram giving eccentric positions.

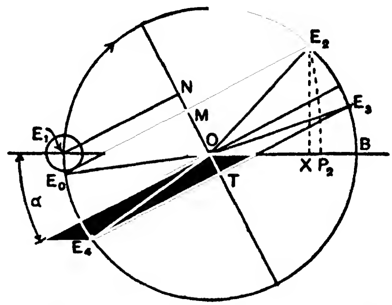


FIG. 82. Valve diagram giving crank positions.

in Fig. 82, and this form of diagram is useful in simple problems on valve positions. The fraction of the stroke, say at cut-off, may be found by obtaining the relative position of the piston P_2 by the construction already given on p. 167. Now, referring to Fig. 82,

$$\text{fraction of stroke at cut-off} = \frac{E_1P_2}{E_1B}.$$

An approximate value would be the ratio $\frac{E_1X}{E_1B}$, where X is the foot of the perpendicular from E_2 on to E_1B, a value which ignores the effect of the connecting rod on the piston positions. The larger the ratio of the length of connecting rod to that of the crank the closer will the points X and P_2 be together.

Example 1. *The throw or eccentricity of an eccentric is $1\frac{5}{8}$ in. The outside lap is $\frac{7}{8}$ in., and there is no inside lap. Determine* (1) *the valve travel,* (2) *the maximum port opening to steam.*

Valve travel $= 2 \times \text{throw} = 2 \times 1\frac{5}{8}$ or $3\frac{1}{4}$ in.

The maximum opening of port to steam occurs when the valve is at the end of its travel, and when it has moved $1\frac{5}{8}$ in. from its mid-position. A travel equal to the outside or steam lap must occur before the port is opened.

$$\text{Hence maximum opening to steam} = \tfrac{1}{2}\text{ travel} - \text{outside lap}$$
$$= 1\tfrac{5}{8}\text{ in.} - \tfrac{7}{8}\text{ in.}$$
$$= \tfrac{3}{4}\text{ in.}$$

Example 2. *A D slide valve has a $\frac{7}{8}$ in. outside or steam lap and the travel of the valve, which just gives a full port opening to exhaust, is $4\frac{1}{8}$ in. Assuming a port opening of $1\frac{5}{8}$ in., calculate the necessary inside or exhaust lap and the maximum steam port opening at this travel.*

Half-travel of valve $= \frac{1}{2} \times 4\frac{1}{8}$ or $2\frac{1}{16}$ in.

To effect a full port opening to exhaust the valve must travel from mid-position a distance equal to the port width plus inside lap.

$$\text{Hence inside lap} \qquad = 2\tfrac{1}{16}\text{ in.} - 1\tfrac{5}{8}\text{ in.} = \tfrac{7}{16}\text{ in.}$$
$$\text{Maximum steam port opening} = \text{half-travel} - \text{outside lap}$$
$$= 2\tfrac{1}{16}\text{ in.} - \tfrac{7}{8}\text{ in.}$$
$$= 1\tfrac{3}{16}\text{ in.}$$

Example 3. *If a lead of $\frac{1}{8}$ in. is given to the valve of the dimensions given in Example 2, determine the angle of advance given to the eccentric.*

If reference is made to Fig. 81,

Outside lap $\mathsf{OM} = \frac{7}{8}$ in. Lead $= \mathsf{MN} = \frac{1}{8}$ in.

Half-travel $= \mathsf{OE_1} = 2\frac{1}{16}$ in.

$$\therefore \text{ sine of angle of advance} = \frac{\mathsf{ON}}{\mathsf{OE_1}} = \frac{1}{2\frac{1}{16}} = \frac{16}{33} = 0{\cdot}4848\,;$$

$\therefore$ angle of advance (from trigonometrical tables) $= 29°$.

Example 4. *Using the principle illustrated by the diagram (Fig. 82), determine graphically the angle of advance of the eccentric and the crank positions at admission, cut-off, release and compression*

Given information,

travel $= 4\frac{1}{8}$ in.,	outside lap $= \frac{7}{8}$ in.,
inside lap $= \frac{7}{16}$ in.,	lead $= \frac{1}{8}$ in.

Draw a circle (Fig. 83) $4\frac{1}{8}$ in. in diameter, with centre O and the diameter E_1OB. With centre E_1 and radius equal to the lead describe a circle. Also with centre O and radius $\frac{7}{8}$ in. equal to the outside lap describe a circle. Now draw a common cross tangent E_0ME_2 cutting the original circle at E_0 and E_2. Join E_0 and E_2 to O, and with centre O draw a circle of $\frac{7}{16}$ in. radius, while through O draw the centre line CD parallel to E_0E_2. Then draw E_4E_3 tangential to the inside lap circle and parallel to CD. Join E_4 and E_3 to O, and then E_1OC is the angle of advance. In this way the position of the crank is obtained for the

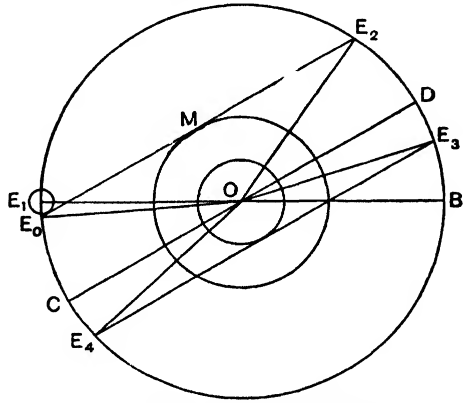


Fig. 83. Valve diagram for Example 4.

main operations; OE_0 is the crank position at admission; OE_2 at cut-off; OE_3 at release and OE_4 at compression or cushioning.

Answers. Angle of advance $= 29°$; admission, $355\frac{3}{4}°$; cut-off, $124\frac{3}{4}°$; release, $161\frac{3}{4}°$; compression, $317\frac{3}{4}°$. All angles measured clockwise from OE_1, except the angle of advance.

Piston Valves. Eccentric operated slide valves do not allow of early cut-off or of variation of cut-off while running. This has led to the introduction of valve gears and link motions of various types with the object of varying the cut-off and for reversing. Improvements in the slide valve itself have been made. The slide valve nowadays is generally replaced by piston valves, or by drop valves after the style of those used in most motor car engines. **Piston valves** work over steam and exhaust ports in much the same way as the slide valve, and the steam control is essentially the same. Piston

valves have steam and exhaust laps as with the slide valve. These valves are usually operated by valve gears, which complicate the treatment.

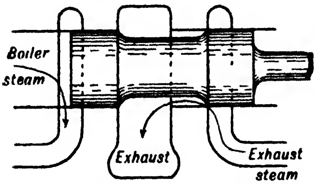


FIG. 84. Piston valve.

A simple type of piston valve is shown in Fig. 84, in a position when it is just closing the right-hand port to exhaust. The valve slides in a cylinder which is fed at each end with boiler steam. Three deep grooves cut in this cylinder serve as entrances for the ports of the main engine cylinder, in such a way that steam can pass circumferentially around the piston valve and equalise the pressure. Thus the piston valve requires less effort to operate it than the unbalanced D type, and brings about a more even distribution of steam.

Stephenson's link motion. This is shown in outline in Fig. 85. OC represents the crank in any position and OE_1 and OE_2 represent the

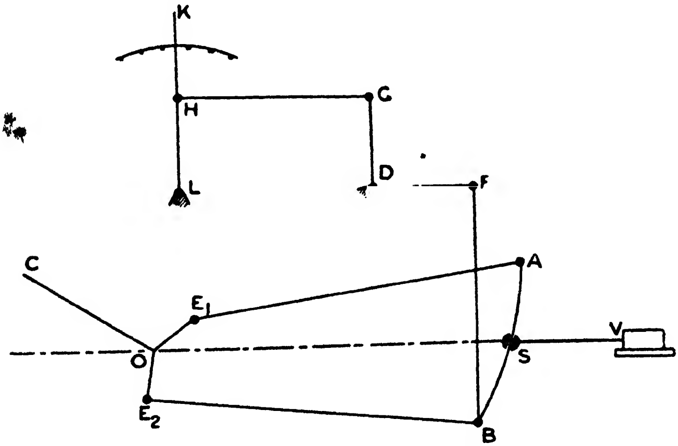


FIG. 85. Diagram of Stephenson's link motion.

centre lines of two eccentrics. If the eccentric OE_1 were connected directly to the valve, the engine would rotate in the opposite direction to that if connected directly to OE_2, since the valve would be driven in opposite directions for corresponding positions of the

piston. The object of the link motion is to use the eccentric OE_1 for one direction of rotation of the crank, and OE_2 for reversing the direction of motion of the engine. In operation the valve rod SV engages with the curved link AB at S by means of a block which may slide in the link. The radius of the link AB is made approximately equal to the length of the eccentric rod employed. A system of levers is used to raise or lower the curved link AB, a bell crank lever GDF pivoted at D being connected to AB by the rod FB, while the bell crank lever is operated by the levers KL and HG. When S and A are close together, the valve receives its motion directly from the eccentric OE_1, the other eccentric OE_2 merely causing the link AB to oscillate without any appreciable effect on the valve motion. When B and S are close together, then eccentric OE_2 has a greater control of the valve motion, and the engine is caused to rotate in the opposite direction.

In any intermediate position of the block S between A and B, both links will contribute towards the motion of the valve. Notching up, or raising, AB from the extreme forward position tends to alter the lead given to the valve, to lessen the travel and diminish the opening to steam, so causing steam admission and other events to occur earlier.

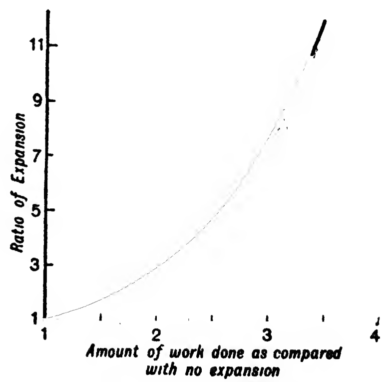


FIG. 86. Value of expansion.

Value of expansion and a high vacuum. The benefits of utilising steam expansion are illustrated by the curve (Fig. 86). These benefits are made possible by the high vacuum created in the condenser, which reduces the back pressure and allows more work to be done in the cylinder. However, it is a disadvantage to carry expansion below the back pressure, as then work has to be done by the engine. The cut-off of the steam supply must not be so early as to bring this about. The great disadvantage of large expansion is the increased condensation of steam in the cylinder due to the cooling action of

low-pressure exhaust steam passing to the condenser prior to the next entry of boiler steam. As the pressure drops towards the end of the stroke, there is a tendency to re-evaporate some of the condensed steam, which still further cools the cylinder. Assuming hyperbolic expansion or $PV=\text{const.}$, the curve (Fig. 86) shows, for the same weight of steam, the proportionate increase in the amount of work done per stroke as the ratio of expansion is increased. Thus for a ratio of expansion of 7·4, three times as much work can be done per lb. of steam with expansion as with no expansion. This, of course, neglects all losses which might occur because of expansion.

Watt's discoveries. Among the developments mentioned in the previous work the following can be attributed to James Watt (1736-1819), the famous Scottish engineer and inventor :

(*a*) the employment of a separate condenser,
(*b*) the introduction of the double-acting engine,
(*c*) expansive working of the steam with the slide valve and early cut off,
(*d*) the governor as a speed control mechanism in the form of the pendulum type of centrifugal governor,
(*e*) the indicator, which will be described later in this chapter.

Means adopted to lessen cylinder condensation. (1) Ensure dry steam entering the cylinder by lagging all pipes and cylinders with non-conducting material to prevent cooling (see Expt. 26) ; also by inserting steam separators, steam traps or steam purifiers in the pipe line near the engine. The pipe line steam purifier works on the same principle as the one described for boiler use in Chap. III.

(2) **Jacketing.** This involves enclosing the cylinder in a steam jacket of boiler steam to prevent excessive cooling. The larger the cylinder, the greater the expansion in it, and the slower the speed of the engine the more important does jacketing become. Although boiler steam is used, it is justified and more than repaid by reducing condensation inside the cylinder, the walls of which are kept hot.

(3) **Superheating the steam.** Condensation is reduced about 1 % for every 8° F. of superheat. Superheated steam must be cooled to below its saturation temperature before it can become wet. This has led to its increasing use in engines and turbines. In addition,

the available heat energy in superheated steam is higher, and a greater heat drop is possible with a larger conversion to mechanical energy.

(4) **Increasing the engine speed.** This means that the steam is not retained so long in the cylinder, and the opportunity for condensation is reduced. Leakage of steam is also reduced.

(5) **Compounding.** This is the name given to the method of allowing the steam to be expanded in two or more cylinders of successively increasing diameters, but of the same stroke or length, the cut-off being adjustable for each cylinder. In this way (*a*) the range of temperature between inlet and exhaust steam is reduced in any one cylinder with a consequent lessening of condensation; (*b*) any re-evaporation which occurs is not lost, but is passed to the next cylinder; (*c*) by arranging a fair distribution of work between the cylinders, these are subjected to less strain on the working parts, and a lighter engine is possible owing to the smaller range of temperature and pressure; (*d*) greater efficiency is possible, since the full expansion of the high-pressure steam can be carried out; (*e*) a more even turning moment can be arranged as each piston drives a different crank, and these can be arranged to give less variation of torque and thus better balance. In compounding, the ratio of expansion allowed in one cylinder is never more than five, and receivers are generally placed between cylinders to serve as steam reservoirs. A triple expansion engine has a high-pressure, an intermediate and a low-pressure cylinder. A 4-stage engine is called a quadruple expansion engine. Reheating the steam in between its passage through the cylinders is sometimes resorted to, in order to increase the effectiveness of the compounding principle. (See p. 189.)

$$\textbf{Ratio of expansion} = \frac{\text{vol. of low-pressure cylinder}}{\text{vol. of high-pressure cylinder up to cut-off}}.$$

Example. *The stroke volumes of the high-pressure and low-pressure cylinders of a compound engine are respectively* $8\frac{1}{3}$ *cu. ft. and* 27 *cu. ft. If cut-off occurs at* $\frac{1}{3}$ *stroke in the high-pressure cylinder determine the ratio of expansion. Neglect clearance.*

$$\text{Ratio of expansion} = \frac{27}{\frac{1}{3}\text{ of }8\frac{1}{3}} = 9{\cdot}72.$$

(6) By adopting the principle of the Uniflow engine.

Uniflow engine. This engine is gradually superseding most types of single cylinder, and compares most favourably with compound engines. As its name applies, the flow of steam is uni-directional and there is no return along the same path, and hence condensation losses are greatly reduced. The steam enters the cylinder at each end in turn and flows or expands towards the centre of the cylinder, where it exhausts through ports. Fig. 87 shows a section through a Uniflow

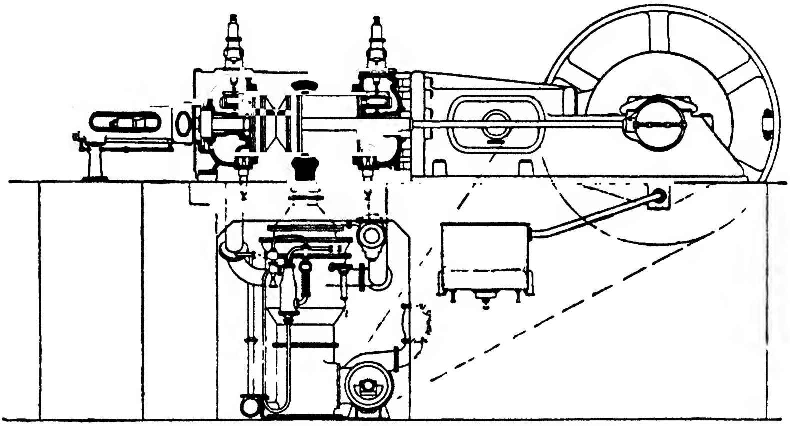


FIG. 87. Sectional view of a Uniflow engine.

cylinder manufactured by Messrs. Hick, Hargreaves & Co. The valves are of the piston drop valve type driven through eccentrics and rods from the lay shaft running at right angles to the crank shaft and geared to it. The governor controls the valves through a trip-gear and arranges the cut-off of the steam in the cylinder up to about 25% of the stroke, thus ensuring ready response to varying loads.

In normal running, cut-off occurs at 10% of the stroke, while expansion follows until 90% of the stroke is completed, when the exhaust ports are opened by the piston. The latter must therefore have a length of 90% of stroke. Steam is exhausted during the 10% of travel to complete the outward stroke and during the first 10% of the return stroke. However, the ports are large and extend

around the cylinder. Compression then follows until the admission valve opens (to lead) just before dead centre is reached. Relief valves are fitted (shown at the bottom at each end of the cylinder) to obviate any dangers which might arise through excessive compression.

Advantages. (1) Condensation is reduced because of the gradual and nearly uniform heat drop towards the cylinder centre, which means less radiation and loss of heat to surrounding air.

(2) Absence of exhaust valves and their replacement by ports allows of small clearance volumes (3% stroke volume), and the high compression obtained reheats the piston head and clearance spaces.

(3) Presence of exhaust ports means a rapid discharge of steam and absence of valve throttling or resistance. Short period of opening of exhaust ports means reduced cooling at this part.

(4) The simplification of the design means fewer parts, less oil consumption and a high mechanical efficiency.

(5) Low steam consumption, especially with high superheat and vacuum (by means of which 9 or 10 lb. of steam per I.H.P. per hour can be obtained).

(6) Although cylinders are large and reciprocating parts must be stronger and heavier than in the compound engine, the inertia of these parts tends to equalise the turning moment on the shaft.

These engines run at between 100 and 200 r.p.m., they are totally enclosed and all bearings have forced lubrication. In the diagram the condenser of the multi-jet type is shown beneath the engine cylinder. Also notice that the piston is provided with a **tail rod**, so that it is supported on both sides.

Intercylinder steam reheating with compound engines. It has been found that reheating the exhaust steam from the high-pressure cylinder before it passes to the low-pressure cylinders of a compound engine leads to an increased engine efficiency. The supply of heat is obtained from steam after it leaves the superheater and before it enters the high-pressure cylinder. A heat exchanger attached to the high-pressure cylinder permits of the exchange of heat, but does not allow the two conditions of steam to mix. In this way the degree of superheat of the steam supplied to the high-pressure cylinder is reduced to about 200° F.,

making the engine easier and cheaper to build and maintain efficiently. Heat exchangers are now employed for triple expansion engines in such a way that the steam is entirely in a superheated state during expansion in the cylinders and is discharged as dry saturated steam, an arrangement which is a very desirable feature for reciprocating engines.

An ordinary steam engine using superheated steam shows a 15% increase in thermal efficiency over the same engine using dry saturated steam ; while it is found that, if the principle of reheating is adopted with an engine using superheated steam, another increase of 10% efficiency may be expected on the superheated steam engine.

The advantages obtained by using intercylinder steam reheaters may be summarised as follows :

(1) No condensation losses and hence an increased thermal efficiency.

(2) The more efficient types of superheater producing steam with a high degree of superheat can be employed.

(3) The difficulties of internal cylinder lubrication are overcome.

NOTE. *Above 630° F. superheated steam rapidly decomposes any suitable lubricant.*

(4) Piston valves can be employed if required.

NOTE. *With high superheat temperatures these valves wear very rapidly.*

(5) Flat slide valves *can* be employed on the intermediate- and low-pressure cylinders.

NOTE. *With high degrees of superheat lubrication breaks down, and too great a strain is thrown on the eccentric rods when the valves run dry. Poppet valves (see p. 235) are generally preferred to slide valves.*

(6) The increased economy and reliability makes their use of value in marine work.

Testing of steam engines. The performance of engines determined as a result of tests provides useful data from which other engines of similar types can be made or built. The testing of engines also enables the engineer to remedy faults and to obtain information as to running costs. Instruments and apparatus are used to make measurements, and from these measurements calculations are made. Measurements are made to determine the

dimensions of cylinders and brake drums, the condition of the working substance and the quantity used, and the energy expended by the working substance and absorbed by the brake, in addition to thermal and mechanical efficiencies.

Power, or the rate of expenditure of energy, is usually recorded under two headings. The power which is developed in the cylinder is called the **indicated horse power** (I.H.P.), because an instrument called an indicator is employed to record the magnitude of the pressure which the working substance exerts on the piston during its motion. **Brake horse power** (B.H.P.) is the power which an engine can produce in external work. Some of the power developed in the cylinder has to be employed in driving the engine itself in overcoming friction. The remainder is called the brake horse power, and thus the B.H.P. is always less than the I.H.P., and their ratio $\frac{\text{B.H.P.}}{\text{I.H.P.}}$ is the **mechanical efficiency.**

A brake which *absorbs* power is called an **absorption dynamometer,** and in this type the mechanical energy output of the engine is converted, as a rule, into either heat or electrical energy. If converted to heat energy, some means must be provided to absorb this heat and keep the brake comparatively cool, and so ensure an even resisting torque or turning moment. The engine may be used to drive a generator of known efficiency, instruments being employed to measure the electrical energy output of the generator. This method, in which the mechanical energy is mostly absorbed and converted to electrical energy, is particularly useful in the testing of steam turbines because the output is not subject to cyclic variations.

The brake horse power of an engine can also be measured while power is being *transmitted*, and in this case the apparatus used is called a **transmission dynamometer.** For example, a shaft, while transmitting power to a machine or to a propeller, becomes slightly twisted from its initial unstrained state, and, within the elastic limits of the material of the shaft, the power transmitted is directly proportional to the angle of twist. By measuring this angle of twist, the horse power transmitted can be calculated when the elastic constant for the material of the shaft is known. Another common form of transmission dynamometer employs a system of pulleys

and belts, and the horse power may be calculated after measuring the belt tensions and pulley speeds.

An **indicator** is an instrument used to record the variation of pressure inside a cylinder with the corresponding positions of the engine piston. The record is made on an **indicator diagram,** the area of which is a scale representation of the amount of work done in the cylinder during a stroke. From this diagram the mean height and M.E.P. are found as described later in this chapter and the I.H.P. calculated. Also by studying the diagrams the engineer can find out if the engine is running efficiently and whether the valve has admitted, cut-off, released and compressed the steam at the correct time. It is easy to see from the diagram the nature of the expansion or compression and the existence of faults, either in working or valve setting, and correction can be made and checked by taking another diagram.

Fig. 88 shows an external spring type indicator by Messrs. Dobbie, McInnes & Clyde, Ltd. The external spring keeps comparatively cool in operation, and its accuracy is not impaired by high-temperature superheated steam. This type is suitable for high pressures and high speeds. It is similar to the Diesel engine indicator shown in Fig. 115, p. 245.

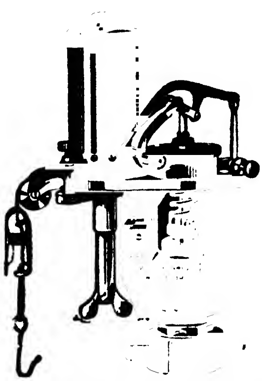


Fig. 88. External spring steam engine indicator.

When steam enters the cylinder it will also enter the cylinder of the indicator through the open cock and exert the same pressure in the indicator piston as on the cylinder. The indicator piston will be forced up and the spring will be compressed, its compression controlling the motion of the piston. The movement of the piston rod operates the parallel motion system of levers shown, which transmit a magnified (6 to 1) vertical movement of the piston to the pointer or pencil in contact with the drum. Hence the vertical movement of the metal pencil is proportional to the steam pressure in the cylinder. The actual movements of the indicator piston are extremely small, and their

inertia does not greatly affect the accuracy of the instrument except at high speeds. If while the piston is moving, the drum holds a piece of sensitised paper and is made to oscillate and follow the motion of the engine crosshead to a reduced scale, an indicator diagram will be drawn on the paper. The motion of the crosshead is transmitted to the indicator drum by means of a wire or cord kept in tension by a spring inside the drum.

Piston leakage is prevented by shallow channels or labyrinths on the outer surface of the piston, which hold water or oil in contact with the cylinder. The springs are carefully made and tested for accuracy. The vulcanite covered caps above the piston chamber and the pressure spring unscrew and allow the piston rod and the parallel motion to be removed bodily for the purpose of changing the spring or cleaning the cylinder. If the edges of the paper are carefully folded, the paper fingers on the outside of the drum will maintain it in position while the diagram is being taken. It will be noticed that the paper fingers or springs on the drum are of different lengths, so that the paper can be easily fitted without creases or wrinkles. Another feature of this indicator is the sheathing, which allows of easy handling at high temperatures.

Fig. 89 shows the patent steel self-lubricating and anti-grit piston with hollow discs. Fig. 90 shows the adjustable drum spring

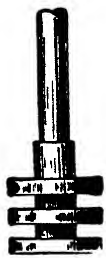


Fig. 89.
Indicator piston.

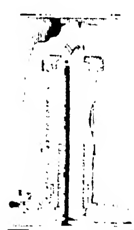


Fig. 90.
Indicator drum and spring.

with brass ends—the spring can be quickly adjusted to give the right tension to suit the engine speed and so prevent backlash. The maximum motion of the drum is about $\frac{3}{4}$ of a revolution, and stops are fitted to prevent this angular travel being exceeded. This drum

spring brings the drum back to one end of its travel, which means that since the return force exerted by the spring varies, the cord tension will also vary throughout the stroke. In consequence the length of the cord operating the drum is made as short as possible to prevent errors in the diagram due to a stretching cord. Fig. 91 shows an indicator cock which connects the indicator to the cylinder. As shown, the cock is open, but when shut, the indicator cylinder is automatically subjected to atmospheric pressure.

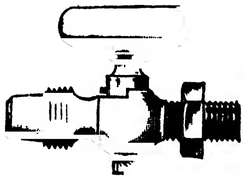


FIG. 91.
Indicator cock.

Fig. 92 shows a simple reduction gear for transmitting the crosshead motion to the indicator drum through the non-stretching cord

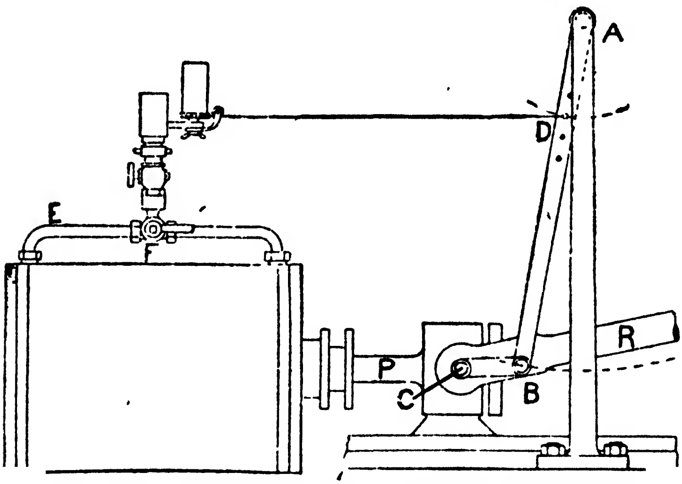


FIG. 92. An arrangement for connecting up and driving an indicator on a steam engine.

shown. It is very important that the reduction be simple and accurate, and that some means be available for readily connecting the indicator to the gear or of throwing it out of action. The diagram shows how the indicator can be used for each end of the cylinder for a double-acting engine, care being taken to see that there are no leaks in the indicator and its connections. There are a

great variety of reduction gears for indicators, many of them giving accurate reductions but having the disadvantage of being complicated, with the consequent increased liability to get out of order. Fig. 93 shows a form of reduction gear which gives greater accuracy and stability than the one shown in Fig. 92.

The ideal conditions to be aimed for in an indicator may be summarised as under :

(1) The rate of rotation of the drum must be proportional to the speed of the engine piston for every position in the stroke.

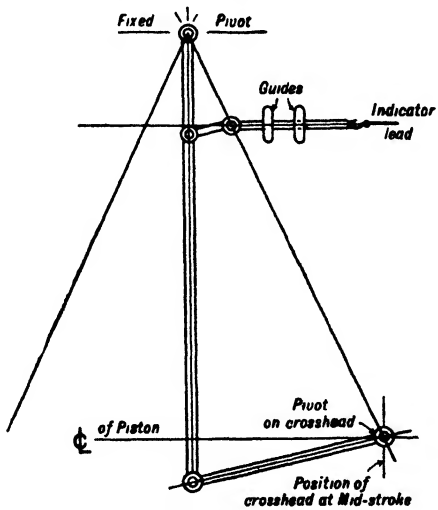


FIG. 93. Reduction gear for an indicator.

(2) The pencil on the indicator must move parallel to the axis of the drum, and its motion must be proportional to the movement of the indicator piston.

(3) The pressure inside the indicator cylinder, at any instant, should be as nearly as possible the same as that within the engine cylinder itself. This is very difficult to obtain in practice, owing to the throttling action and condensation losses in the indicator pipes.

(4) The spring should be subjected to a cooling influence to facilitate a uniform stiffness. For this reason, external spring indicators,

that is, indicators in which the spring is constantly in contact with the cooling effect of the outside air, are now preferred.

A certain amount of dexterity is necessary in obtaining a diagram, and the following points should be noted.

(1) See that the spring is suitable for the maximum pressure and speed of the engine, and that it is firmly fitted. On each spring the pressure in lb. per sq. in. necessary to move the indicator pencil 1 in. is stamped. The maximum pressure that the spring can safely carry is also frequently stamped on it, to prevent damage or fracture.

(2) See that the motion of the drum is such that there is no knocking of the stops at either end of the stroke.

(3) See that the drum spring is adjusted to maintain tautness in the cord at high speeds.

(4) Carefully fold over about $\frac{1}{4}$ in. of the short end or edge of the paper, and place one end of the crease so formed against the top of the inner edge of the longer finger on the drum. Wrap the paper round the top of the drum, and insert the other short edge behind and around the top short finger. Then push the paper down into position and fold the short edges of paper against the fingers. In this way the paper is placed on the drum so that the indicator fingers hold it securely.

(5) Connect the indicator to the reducing gear, and press the pencil lightly on the paper while the engine is running and the cock closed. In this case the piston is in contact with the atmosphere, so that a straight line is marked on the card, called the atmospheric line. The indicator cock may now be opened and shut a few times to allow steam to enter the indicator cylinder and warm it, and also blow out any water which may have collected.

(6) Assuming the condition of the engine has been allowed to become steady, open the indicator cock smartly and press pencil lightly against the paper sufficiently long for at least one cycle of events. Repeat for the other end of the cylinder, and record the engine speed, brake reading of engine and stiffness of spring (or any other information required) at the same time. Throughout the proceedings take every precaution to keep the indicator card as clean as possible.

(7) At the completion of the test carefully remove the indicator spring, then clean and oil it to avoid corrosion.

Determination of indicated horse power. Since the indicator diagram records the variation of steam pressure acting on the piston throughout its stroke, the average height of the diagram will record the mean effective pressure. The pressures represented by the line ABC (Fig. 94) give the variation in pressure on the boiler side of the piston, and the pressures represented by the line CDA give the variation in pressure on the exhaust side at any point during the stroke. Thus the height of the diagram PQ at any point R, measured at right angles to the atmospheric pressure line, will represent the

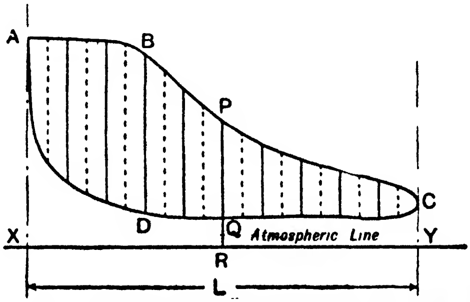


FIG. 94. Indicator diagram showing mid-ordinates.

effective pressure acting on the piston. A $\frac{1}{80}$ spring means that 1 inch on the pressure scale of the diagram represents 80 lb. per sq. in. cylinder pressure. Therefore the effective pressure at R is

$$PQ \times 80 \text{ lb. per sq. in.,}$$

where PQ is measured in inches and XR/XY is the fraction of the stroke completed by the piston.

The distance L between the perpendiculars AX and YC to the atmospheric line, which are drawn to touch the extremities of the diagram, should be carefully measured in inches and divided into a number of equal divisions shown by the full lines similar to PQ. Mid-ordinates are drawn dotted between these division lines, and these are measured and the sum of their lengths found. When this total is divided by the number of mid-ordinates a figure representative of the average height of the diagram, that is, the height of the

equivalent rectangle is obtained. This average height in inches must then be multiplied by the scale figure corresponding to the spring employed in the indicator to give the **mean effective pressure (M.E.P.).**

Another and better method (already dealt with in Example 1, p. 172), if a planimeter is available, is to measure the area of the diagram in square inches by means of the planimeter, and then divide this area by the length of the diagram L to obtain the average height and the mean effective pressure as before.

The two methods of determining the mean effective pressure, which have just been given, are those most frequently employed.

$$\text{Now I.H.P.} = \frac{\text{work done in the cylinder in ft. lb. per min.}}{33{,}000}$$

$$= \frac{\text{average work done per working stroke} \times \text{no. of effective strokes per min.}}{33{,}000}$$

The average work done per working stroke is given by the product :

$$\begin{pmatrix}\text{Mean effective pressure}\\ \text{in lb. per sq. in. (P)}\end{pmatrix} \times \begin{pmatrix}\text{area of piston}\\ \text{in sq. in. (A)}\end{pmatrix} \times \begin{pmatrix}\text{length of stroke}\\ \text{in ft. (L).}\end{pmatrix}$$

The number of effective strokes per minute is the same as the number of revolutions per minute (N) made by the engine in a single-acting engine, and twice that number for a double-acting engine.

In the case of double-acting steam engines, with or without tail rods, it is customary, and more accurate, to deduct the area of the piston rod or tail rod from the total piston area, *i.e.* the cross-sectional area of the cylinder, for the side of the piston concerned.

NOTE. *A tail rod is an extension to the back of the piston, used frequently in horizontal engines to prevent the weight of the piston acting without restraint on the cylinder walls.*

The expression for I.H.P. is often given as

$$\frac{a\,\text{PLAN}}{33{,}000},$$

where $a = 1$ for single-acting engines,
$\quad = 2$ for double-acting engines,

and P is the mean effective pressure for both sides of the piston, and N is the number of revolutions per minute.

For double-acting engines and when P is an average value for both sides of the piston, then A should be taken as the average of the effective areas for the two sides of the piston, after allowance has been made for the piston rod.

When the indicator diagrams for both sides of the piston are given, it is customary to determine the indicated horse power for each side of the piston separately and then add the results. Example No. 3 will illustrate this point.

Example No. 1 shows how three factors influence the scale of an indicator diagram. These factors are: (1) the stiffness of the indicator spring, (2) the area of the indicator piston, and (3) the ratio between the travel of the pencil and the indicator piston.

Example 1. *The stiffness of a spring used for a certain indicator was found, by axially loading the spring with weights, to be 576 lb. per inch of compression. The area of the indicator piston was 1 sq. in., and the parallel link motion on the indicator was such that the pencil travel was 6 times that of the indicator piston. Find the pressure scale of an indicator diagram obtained by using this indicator and spring.*

For 1 inch movement of the pencil the piston moves $\frac{1}{6}$ in.

The motion of the piston is controlled by the spring, which must be compressed $\frac{1}{6}$ in.

Hence, load on spring $= \frac{1}{6} \times 576$ or 96 lb.

At this load the intensity of pressure on the indicator piston

$$= \frac{\text{load on piston}}{\text{area of piston}} = \frac{96 \text{ lb.}}{1 \text{ sq. in.}} = 96 \text{ lb. per sq. in.}$$

Indicator scale is **96 lb. per sq. in. per in.**

Example 2. *Find the approximate ratio of* AB *to* AD *for the reducing gear illustrated in Fig. 92, from the particulars given below.*

Radius of indicator drum measured to centre of operating cord $= 1\frac{1}{8}$ *in.*

Available motion of drum $= \frac{3}{4}$ *rev. Stroke of engine* $= 30$ *in.*

The motion of the point D is to be $2\pi \times 1\frac{1}{8} \times \frac{3}{4}$ in. or 5·36 in. per stroke of the engine, while the motion of the point B is approximately 30 in., measured horizontally in both cases.

Hence ratio of lengths, being proportional to the travel of the points concerned, is $\frac{AB}{AD} = \frac{30}{5 \cdot 36} = 5 \cdot 6$.

$\therefore$ AB must be made 5·6 times the length of AD.

Example 3. *The indicator diagrams shown in Fig. 95 are taken for each end of the high-pressure cylinder of a compound and double-acting steam engine. The cylinder diameter was 22 in. and the stroke 45 in. and the piston rod $3\frac{1}{2}$ in. in diameter. Calculate the indicated horse power of the engine if the crank shaft revolves at 144 r.p.m.*

Method 1. By measuring the mid-ordinates and finding the average, the mean height of the diagram for boiler steam action at the cover or

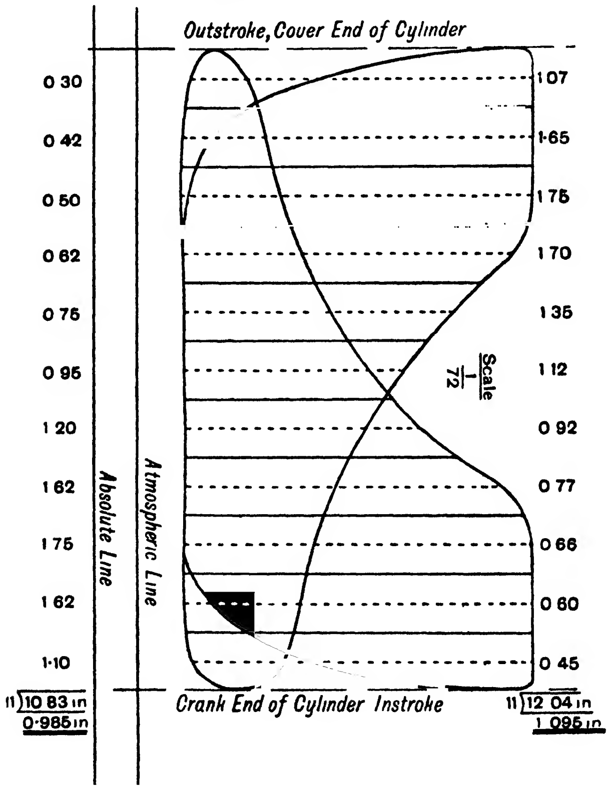


FIG. 95. Method of obtaining the mean height of indicator diagrams.

cylinder end of the engine is found to be 1·095 in., representing a mean effective pressure of

$$1{\cdot}095 \times 72 \text{ or } 78{\cdot}84 \text{ lb. per sq. in.}$$

Area of piston $= \pi \times 11^2 = 380{\cdot}1$ sq. in.

Average work done per stroke $= 78{\cdot}84 \times 380{\cdot}1 \times 45 \div 12$.

I.H.P. for cover end $= \dfrac{78{\cdot}84 \times 380{\cdot}1 \times 45 \times 144}{33{,}000 \times 12}$, *i.e.* $\dfrac{\text{PLAN}}{33{,}000}$

$= 490{\cdot}4$.

For the **crank end**,

area of piston − area of rod $= 380{\cdot}1 - \pi \times (1\tfrac{3}{4})^2$

$= 370{\cdot}4$ sq. in.

Mean effective pressure $= 0{\cdot}985 \times 72$ or $70{\cdot}92$ lb. per sq. in.

$\therefore$ I.H.P. for crank or gland end $= \dfrac{70{\cdot}92 \times 370{\cdot}4 \times 45 \times 144}{33{,}000 \times 12}$

$= 429{\cdot}8$.

Total indicated horse power $= 490{\cdot}4 + 429{\cdot}8 = 920{\cdot}2$.

Method 2. To find the area of the diagrams by means of a planimeter. Length of diagram $= 3{\cdot}3$ in.

Cover or cylinder end.

Area by planimeter = difference of readings of instrument

$= 29{\cdot}83 - 26{\cdot}23$ or $3{\cdot}6$ sq. in.

$\therefore$ average height $= \dfrac{3{\cdot}6 \text{ in.}^2}{3{\cdot}3 \text{ in.}} = 1{\cdot}091$ in., which represents a mean effective pressure of $1{\cdot}091 \times 72$ or $78{\cdot}55$ lb. per sq. in.

This gives I.H.P. for cover end as $488{\cdot}7$.

Crank end. Area by planimeter $= 12{\cdot}23 - 9{\cdot}00$ or $3{\cdot}23$ sq. in.

$\therefore$ average height $= \dfrac{3{\cdot}23 \text{ in.}^2}{3{\cdot}3 \text{ in.}} = 0{\cdot}9788$ in., which represents a mean effective pressure of $0{\cdot}9788 \times 72$ or $70{\cdot}47$ lb. per sq. in.

This gives I.H.P. for crank end as $427{\cdot}2$.

total horse power $= 488{\cdot}7 + 427{\cdot}2 = 915{\cdot}9$.

Example 4. *The piston diameter and stroke of a double-acting steam engine are respectively* 24 *in. and* 36 *in. and the piston rod* $3\tfrac{1}{2}$ *in. in diameter. If the mean effective pressure for both ends of the cylinder is given as* 39·4 *lb. per sq. in., determine the indicated horse power at* 90 *r.p.m.,* (*a*) *assuming a tail rod of* $3\tfrac{1}{2}$ *in. diameter, and* (*b*) *without a tail rod.*

(*a*) Effective area of piston on both sides $= \pi \times 12^2 - \pi \times (1\tfrac{3}{4})^2$

$= \pi \times 13\tfrac{3}{4} \times 10\tfrac{1}{4}$

$= 442{\cdot}8$ sq. in.

Using the formula, I.H.P. $= \dfrac{2\,\text{PLAN}}{33{,}000}$ where $a = 2$

$= \dfrac{2 \times 39{\cdot}4 \times 3 \times 442{\cdot}8 \times 90}{33{,}000} = 285{\cdot}5$.

(*b*) Without a tail rod, area of piston at cover end $= \pi \times 12^2$ or 452·4 sq. in.

Hence, average of effective areas $= \frac{1}{2}(442{\cdot}8 + 452{\cdot}4)$ or 447·6 sq. in.

In this case I.H.P. $= \dfrac{2 \times 39{\cdot}4 \times 3 \times 447{\cdot}6 \times 90}{33{,}000} = 288{\cdot}6.$

Brake horse power. A common form of rope brake for small power engines is shown in Fig. 96. This form of brake absorbs the mechanical energy output of the engine and dissipates it as heat energy to cooling water and to the atmosphere. A double rope in the form of an endless loop is passed around the brake or flywheel

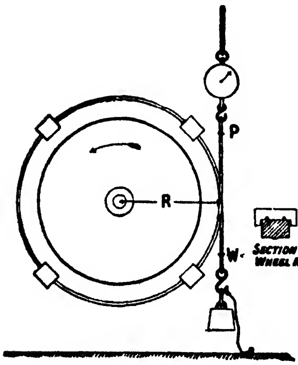


Fig. 96. A common form of rope brake.

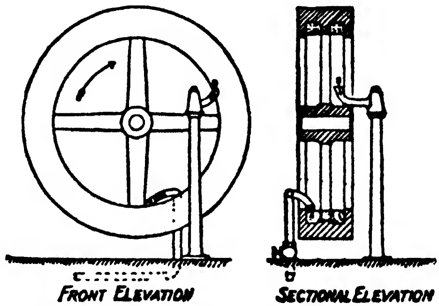


Fig. 97. Arrangement for water-cooling brake wheel rim.

and kept in position (see separate view) by means of wooden blocks, to which the ropes are wired or nailed, and which fit loosely on the flywheel rim. One light or looped end is connected to a weight or a system of slotted weights on a carrier, and the other looped end is taken up to a spring balance hung from a suitable support. The wooden blocks are often made of poplar, as this is a suitable wood to withstand the conditions of wear and temperature of working. To make the ropes supple they should be impregnated with graphite paste lubricant, or alternatively a mixture of tallow and blacklead may be used. Cotton ropes are generally chosen, and it is important to see that they are sufficiently strong for the purpose in hand.

Fig. 97 shows an arrangement for cooling a brake wheel. The rim is made of channel section, so as to hold water on its inner sur-

face; the speed of the wheel and the centrifugal action ensuing maintains the water against the inner rim throughout the whole circumference and prevents it falling from the wheel. Fresh water is supplied continually near the bottom of the wheel, and a sharp-edged scoop removes and drains away the excess water. In this way a continuous supply of fresh cooling water reaches the brake and maintains even temperature working conditions, and so tends to maintain the resisting torque on the engine as uniform as possible.

To calculate the work absorbed by the brake, it should be observed that the force indicated by the spring balance assists the rotation of the wheel, while gravity, acting on the mass W lb., prevents rotation of the brake in the direction of the arrow (Fig. 96). The kinetic friction, or friction of motion, between the rope and the rim communicates these forces to the wheel.

Hence the effective force tending to prevent rotation $= (W - P)$ lb.

Taking R ft. as the distance from the shaft centre to the centre of the rope,

$$\text{work done by engine per revolution} = (W - P) \times 2\pi R \text{ ft. lb.}$$

$$\text{Then B.H.P.} = \frac{\text{work done by engine per min. at the brake}}{33{,}000}$$

$$= \frac{(W - P) \times 2\pi RN}{33{,}000}, \text{ where } N = \text{rev. per min.}$$

A modification of the Froude hydraulic brake or absorption dynamometer made by Messrs. Heenan & Froude, Ltd., is a very popular and efficient form of brake, as it can be used over a large range of speed and for absorbing small or large powers. The brake consists of two main parts, which are generally referred to as the stator and the rotor; the engine to be tested is coupled directly to a rotor, while the casing or stator is mounted on anti-friction trunnions or supports. In the modified form of brake, water flows continuously through the semicircular-shaped pockets in the stator to similar pockets in the rotor, in a direction designed to set up an even resistance to the motion of the latter. The motion of the rotor is continuous, and there is a tendency to drag the stator around with the rotor. This tendency is indicated and measured on a weighing mechanism fitted at a known distance from the centre of the rotor. The passages or pockets of both stator and rotor are

kept full of water. To alter the load on the engine the resistance may be increased or lessened by an adjustable rotating sluice operating between the stator and the rotor, in such a way that it uncovers or covers more water passages or pockets, and so increases or decreases the resistance to motion.

Example. *Determine the brake horse power of an engine from the following observed data.*

Average engine speed $= 221{\cdot}2$ *r.p.m.*
Magnitude of dead load $= 70$ *lb.*
Mean spring balance reading $= 14{\cdot}4$ *lb.*
Diameter of brake drum between rope centres $= 2$ *ft.* 3 *in.*

$$\text{B.H.P.} = \frac{\text{work absorbed per min.}}{33{,}000}$$
$$= \frac{(70 - 14{\cdot}4) \times \pi \times 2{\cdot}25 \times 221{\cdot}2}{33{,}000} = 2{\cdot}63.$$

Willans' law. In the case of a reciprocating steam engine or a turbine governed by throttling the steam supply, *i.e.* by controlling the quantity reaching the engine by means of a valve placed near the steam chest, and when the point of cut-off in the case of the reciprocating engine is kept constant, the increase in the total steam consumption is found to be directly proportional to the increase in the power developed as far as the maximum output. In other words, the steam consumption plotted against the horse power developed gives a straight line graph which does not pass through the origin. This relationship holds very well, whether the steam is saturated or superheated and whether brake or indicated horse power is taken, and is known as Willans' law. Willans was the first to point out this relationship, and the straight line graph so produced is known as a Willans' line.

* **Example.** *After plotting a series of test results of brake horse power readings* (P) *against steam consumption* (S) *in lb. per hour a straight line graph was obtained. The co-ordinates of two points on the graph were* (7·5, 510) *and* (45, 1183). *Determine the equation of the Willans' line. Also find the rate of steam consumption in lb. per B.H.P. hour when the B.H.P. is* 40.

The equation will be $S = mP + c$ ....(1)
in which m and c are constants for a straight line graph.

Substituting the values of the given points in (1),

$$\begin{aligned} 1183 &= 45\ \ m + c \\ \underline{510} &= \underline{\ 7{\cdot}5m + c} \end{aligned}$$

Subtracting, $673 = 37{\cdot}5m$

whence $m = 17{\cdot}95$

and $c = 375{\cdot}4$

Hence the law is $\mathsf{S} = \mathbf{17{\cdot}95P + 375{\cdot}4}$.

This equation shows that when P is 0, S has the value 375·4 lb. per hour. In other words, the engine requires 375·4 lb. of steam each hour to keep it running at the test speed without doing any external work. This constant drain on the boiler steam supply is due to condensation, leakage, and running losses when not under load.

The steam consumption in lb. per hour per B.H.P.

$$= \frac{\mathsf{S}}{\mathsf{P}} = \frac{17{\cdot}95\mathsf{P}}{\mathsf{P}} + \frac{375{\cdot}4}{\mathsf{P}} = 17{\cdot}95 + \frac{375}{\mathsf{P}}.$$

When $\mathsf{P} = 40$, this becomes $17{\cdot}95 + \frac{375}{40}$ or **27·34 lb. per B.H.P. hour.**

Heat received by an engine and its relation to brake horse power. The amount of steam supplied to the engine is usually taken as the weight of steam condensed in the condenser and jackets. In addition, the pressure and temperature (if superheated) of the steam supply to the engine must be recorded by gauge in a simple engine test. In this way the heat taken in by the engine per minute can be calculated with the help of steam tables. The heat supplied is usually reckoned *above the liquid heat of the exhaust*.

The **thermal efficiency** of an engine is the ratio :

$$\frac{\text{heat converted to mechanical work}}{\text{heat supplied}}.$$

Engine efficiencies. The mechanical efficiency has already been defined on p. 191, and can easily be found when the B.H.P. and I.H.P. are known. It is the ratio $\frac{\text{B.H.P.}}{\text{I.H.P.}}$, or more accurately

$$\frac{\text{work performed at the crank shaft}}{\text{work done in cylinder in same time}}.$$

The thermal efficiency with regard to the heat supplied in the steam can be found as follows :

$$\text{Heat equivalent of B.H.P.} = \frac{\text{B.H.P.} \times 33{,}000}{778} \text{ B.Th.U. per min.}$$

Total heat supplied to engine per min.

$$= \begin{pmatrix}\text{wt. of steam} \\ \text{in lb. per min.}\end{pmatrix} \times \begin{pmatrix}\text{total heat per lb.} \\ \text{above liquid heat of exhaust.}\end{pmatrix}$$

Then **brake thermal efficiency** $= \dfrac{\text{useful work done}}{\text{total energy supplied}} \times 100$

$$= \frac{\text{heat equivalent of B.H.P.}}{\text{total heat per min.}} \times 100.$$

The **indicated thermal efficiency** can be found in a similar way.

$$\text{Indicated thermal efficiency} = \frac{\text{heat equivalent of I.H.P.}}{\text{total heat per min.}} \times 100.$$

Example 1. *A double-acting steam engine has a single cylinder* 12 *in. in diameter and a stroke of* 17 *in. Indicator cards taken with a* $\frac{1}{64}$ *spring gave an average area of* 2·84 *sq. in. and an average length of* 3·02 *in. Calculate the mean effective pressure and the indicated horse power if the mean speed was* 135 *r.p.m.*

Calculate the brake horse power and the mechanical efficiency if the dead load on the rope brake was 560 *lb., the spring balance reading is* 56 *lb., and the diameter of the rope brake measured to the rope centre is* 10 *ft.*

Average height of indicator diagram $= \dfrac{2{\cdot}84}{3{\cdot}02} = 0{\cdot}94$ in.

$\therefore$ Mean effective pressure with $\frac{1}{64}$ spring $= 64 \times 0{\cdot}94$

$= 60{\cdot}2$ **lb. per sq. in.**

Average force on piston $= \pi \times 6^2 \times 60{\cdot}2 = 6808$ lb.

Work done per stroke $= 6808 \times 17 \div 12$ or 9645 ft. lb.

$$\therefore \text{ I.H.P.} = \frac{9645 \times \text{no. of strokes}}{33{,}000} = \frac{9645 \times 270}{33{,}000}$$

$= 78{\cdot}9.$

Work absorbed by brake per rev. $= (560 - 56) \times 5 \times 2\pi$ ft. lb.

$= 15{,}833$ ft. lb.

H.P. absorbed $= \text{B.H.P.} = \dfrac{15{,}833 \times 135}{33{,}000} = 64{\cdot}77.$

Mechanical efficiency $= \dfrac{64{\cdot}77}{78{\cdot}9} \times 100 = 82{\cdot}1\%.$

Example 2. *In a test on an engine consisting of 2 double-acting cylinders of 28 in. diameter and 40 in. stroke, the following figures were obtained :*

Steam supply, 160 lb. per sq. in. abs. and dry. Cut-off, 0·7 stroke.
R.P.M., 64. Back pressure, 5 lb. per sq. in. abs.
From indicator cards, mean effective pressure, 92 lb. per sq. in.

Calculate (1) the maximum force on the pistons, (2) the diagram factor, and (3) the indicated horse power.

(1) Maximum force on pistons = maximum steam pressure × area of piston

$$= 160 \times \pi \times 14^2$$
$$= \mathbf{98{,}510\ lb.}$$

(2) In this case the ratio of expansion $r = \frac{1}{0 \cdot 7}$ or 1·429.

Theoretical mean effective pressure $= p_m = p_1\left(\frac{1 + \log_e r}{r}\right) - p_b$

$$= 160\left(\frac{1 + \log_e 1 \cdot 429}{1 \cdot 429}\right) - 5 = 160\left(\frac{1 + 2 \cdot 3026 \log_{10} 1 \cdot 429}{1 \cdot 429}\right) - 5$$
$$= 146 \cdot 9 \text{ lb. per sq. in.}$$

Actual mean effective pressure = 92 lb. per sq. in.

$$\therefore \text{ diagram factor} = \frac{92}{146 \cdot 9} = \mathbf{0 \cdot 626.}$$

(3) $$\text{I.H.P.} = \frac{\text{work done in 2 cylinders per min.}}{33{,}000} \text{ or } \frac{2 \times 2\ \text{PLAN}}{33{,}000}$$

$$= \frac{92 \times \pi \times 14^2 \times 40 \times 64 \times 2 \times 2}{33{,}000 \times 12} = \mathbf{1465.}$$

Example 3. *Determine the brake horse power of an engine from the following observations obtained by means of a brake of the Prony type :*

Net brake load acting at a radius of 30 in., 55 lb.
Mean speed, 360 r.p.m.

If 15 lb. of cooling water were supplied per minute to the brake and the temperature of the water was raised from 56° F. on entering to 80·5° F. on leaving. Calculate the quantity of heat absorbed by the cooling water and the quantity dissipated to the atmosphere.

Work absorbed by brake per rev. $= 55 \times \pi \times 2\frac{1}{2} \times 2$
$= 863 \cdot 5$ ft. lb.

$$\text{B.H.P.} = \frac{\text{work absorbed by brake per min.}}{33{,}000} = \frac{863 \cdot 5 \times 360}{33{,}000} = \mathbf{9 \cdot 42.}$$

Heat equivalent of B.H.P. $= \dfrac{9{\cdot}42 \times 33{,}000}{778}$ B.Th.U.

$= 399{\cdot}4$ B.Th.U.

This is the heat absorbed by the cooling water and the atmosphere.

Heat absorbed by cooling water $= 15 \times (80{\cdot}5 - 56)$

or **367·5 B.Th.U. per min.**

Heat dissipated to atmosphere

$= 399{\cdot}4 - 367{\cdot}5$ or **31·9 B.Th.U. per min.**

Example 4. *The diameter and stroke of a single-cylinder double-acting steam engine are respectively* 18 *in. and* 27 *in. Steam is supplied at* 200 *lb. per sq. in. abs. dry and exhausted at* 4 *lb. per sq. in. abs,, while the engine runs at* 160 *r.p.m. with normal load and cut-off at half-stroke. Calculate the indicated horse power on normal load, allowing a diagram factor of* 0·88.

Assuming the mechanical efficiency to be 80% *and the actual steam consumption to be* 50% *greater than the theoretical steam consumption, estimate the probable steam consumption in lb. per B.H.P. per hour.*

Theoret. mean effective pressure $= p_m = p_1 \left(\dfrac{1 + \log_e r}{r}\right) - p_b$

$$= 200 \left(\frac{1 + \log_e 2}{2}\right) - 4$$

$$= 200 \left(\frac{1 + 2{\cdot}3026 \log_{10} 2}{2}\right) - 4$$

$$= 200 \left(\frac{1{\cdot}6931}{2}\right) - 4 = 165{\cdot}3 \text{ lb. per sq. in.}$$

Actual mean effective pressure $= 0{\cdot}88 \times 165{\cdot}3 = 145\ 5$ lb. per sq. in.

Work done per min. $= 145{\cdot}5 \times \pi \times 9^2 \times \dfrac{27}{12} \times 160 \times 2$

$= 26{,}660{,}000$ ft. lb.

I.H.P. $= \dfrac{26{,}660{,}000}{33{,}000} = 807{\cdot}8.$

B.H.P. $= \dfrac{80}{100} \times 807{\cdot}8 = 646{\cdot}2.$

Vol. of steam required per stroke $= \frac{1}{2}$ vol. of cylinder, if clearance is neglected.

Vol. of steam required per hour $= \dfrac{150}{100} \times \dfrac{\pi \times 9^2 \times 27}{2 \times 1728} \times 160 \times 2 \times 60$

$= 57{,}270$ cu. ft.

Vol. of 1 lb. of dry saturated steam at 200 lb. per sq. in. (from tables)

$$= 2{\cdot}293 \text{ cu. ft.}$$

$$\therefore \text{ Wt. of steam required per hour} = \frac{57{,}270}{2{\cdot}293} \text{ lb.} = 24{,}980 \text{ lb.}$$

$$\text{Wt. of steam per B.H.P. per hour} = \frac{24{,}980}{646{\cdot}2} \text{ lb.} = \mathbf{38{\cdot}67 \text{ lb.}}$$

Example 5. *Calculate the I.H.P., B.H.P., mechanical and thermal efficiencies, and steam per B.H.P. per hour from the data summarised below. All figures are taken as an average during a half-hour test.*

Piston dia. $= 7\frac{1}{2}$ *in. Stroke* $= 10$ *in. R.P.M.* $= 206$. *Average mean effective pressure for the two sides of a double acting engine* $= 34{\cdot}62$ *lb. per sq. in. Average effective brake load* $= 179$ *lb. Average radius of load* $= 21{\cdot}25$ *in. Total weight of steam condensed* $= 217{\cdot}5$ *lb. Initial pressure of steam supply* $= 90$ *lb. per sq. in. Dryness fraction* $= 0{\cdot}94$. *Temperature of condensed steam* $= 57°$ *C.*

Area of piston (neglecting rod) $= \dfrac{\pi \times (7\frac{1}{2})^2}{4} = 44{\cdot}15$ sq. in.

I.H.P. Work done per stroke $= 44{\cdot}15 \times 34{\cdot}62 \times \dfrac{10}{12} = 1274$ ft. lb.

Work done per min. $= 1274 \times 206 \times 2 = 524{,}777$ ft. lb.

Indicated horse power $= \dfrac{524{,}777}{33{,}000} = \mathbf{15{\cdot}9}$.

Heat equivalent of indicated work per min.

$$= 524{,}777 \div 1400 = 374{\cdot}8 \text{ C.H.U.}$$

B.H.P. Work done per revolution $= 179 \times 2\pi \times 21{\cdot}25 \div 12 = 1992$ ft. lb.

Work done per min. $= 1992 \times 206 = 411{,}000$ ft. lb.

Brake horse power $= \dfrac{411{,}000}{33{,}000} = \mathbf{12{\cdot}46}$.

Heat equivalent of brake work per min.

$$= 411{,}000 \div 1400 = 293 \text{ C.H.U.}$$

$$\text{Mechanical efficiency} = \frac{\text{B.H.P.}}{\text{I.H.P.}} \times 100 = \frac{12{\cdot}46}{15{\cdot}9} \times 100 = \mathbf{78{\cdot}3\%}.$$

Total steam supplied per hour $= 217{\cdot}5 \times 2 = 435$ lb.

Steam supplied per B.H.P. per hour $= \dfrac{435}{12{\cdot}46} = \mathbf{34{\cdot}91 \text{ lb.}}$

Heat in 1 lb. of steam as supplied to engine

$$= 0{\cdot}94 \times 499 + 161{\cdot}35$$

$$= 630{\cdot}4 \text{ C.H.U. (see tables).}$$

Heat in 1 lb. of condensed steam $= 57$ C.H.U.

Heat supplied to engine per lb. $= 630{\cdot}4 - 57 = 573{\cdot}4$ C.H.U.

Steam supplied per min. $= \dfrac{217{\cdot}5}{30} = 7{\cdot}25$ lb.

Heat supplied to engine per min. $= 7{\cdot}25 \times 573{\cdot}4 = 4157$ C.H.U.

$$\text{Brake thermal efficiency} = \frac{\text{heat to work}}{\text{heat supplied}} = \frac{293}{4157}$$

$$= 0{\cdot}0705 \text{ or } 7{\cdot}05\%.$$

$$\text{Indicated thermal efficiency} = \frac{\text{heat equivalent of indicated work}}{\text{heat supplied}}$$

$$= \frac{374{\cdot}8}{4157} = 0{\cdot}09 \text{ or } 9{\cdot}0\%.$$

Turbines. The **de Laval turbine**, invented by the Swedish engineer de Laval in 1887, is still used, although in slightly modified forms, to drive fans, blowers, pumps and dynamos through reduction gearing.

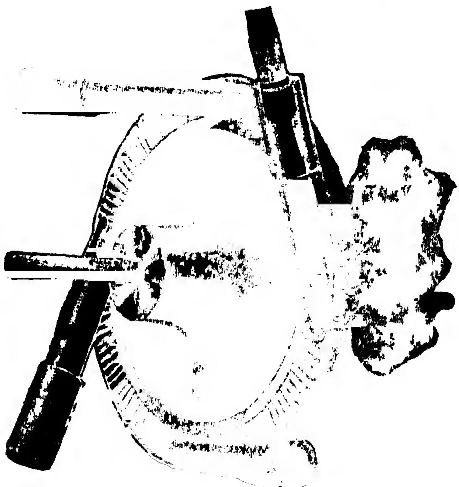


FIG. 98. Action of the de Laval steam turbine.

In this turbine steam expands in fixed nozzles, acquires a very high velocity, and is then directed on to the blades or vanes on the rotor. The action is shown in Fig. 98. The curved surfaces of the blades

deflect the steam jet forcibly, and at the same time receive an impulse in the reverse direction. Although the velocity of the steam jet becomes greatly reduced, the pressure on both sides of the wheel is the same. The shape of the blades is arranged to permit the steam to impinge without shock. In modern designs the wheel is solid and the flexible shaft is bolted to the wheel to give added strength. Only small sizes are made, with one ring of blades or vanes, and these turbines are always run at speeds well above that at which the shaft would "whip" or whirl.

A nozzle and screw down shut-off valve of a de Laval turbine are shown in Fig. 99. In this way the steam supply can be controlled

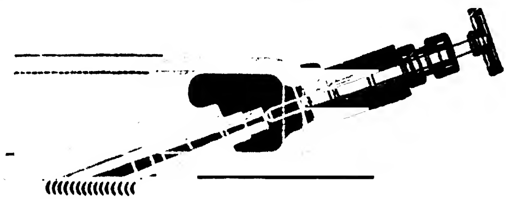


FIG. 99. Nozzle and shut-off valve and vanes.

independently of the governor, each nozzle being fitted with a valve. It is the function of the nozzle to convert the heat and pressure energy of the steam into a corresponding amount of kinetic energy, *which is proportional to the square of the speed.* The essential feature of a nozzle is a throat, connecting a region of low with a region of high pressure, and it is necessary to make the change in cross-section of the passage gradually, so that the conversion of energy is as complete as possible. On the low-pressure side of the throat the nozzle is often made conical with a cone angle of 10°. Ignoring losses, the energy equation is

loss of heat energy or heat drop of steam = gain of kinetic energy.

In the turbine itself, provided there is no change of pressure, then

initial kinetic energy = final kinetic energy + losses + work done.

Actually windage, steam friction over blades and wheel, eddy losses and bearing friction cause losses of kinetic energy, which is reconverted back into heat energy and is not recovered. It must

be remembered that with turbines the impulse is given to the rotor, but that the equal and opposite reaction is taken by the nozzles and turbine casing or stator.

Impulse turbines. In the Curtis and Rateau turbines efforts have been made to utilise the high residual velocity of the steam that issues from the de Laval turbine wheel, by directing this steam on to moving vanes on other rotors. Curtis used rows of fixed blades to redirect the steam, while Rateau used nozzles, as many as 15 series of de Laval wheels and nozzles being mounted on one shaft. The types of turbine mentioned are called impulse turbines, because of the impulse or direct thrust which the steam gives to the rotor. Impulse turbines are distinguishable by the fact that both fixed and moving blades are not convergent, that is, there is no alteration in the size of steam passage through the blades. This principle, adopted by Rateau and Curtis, is referred to as *velocity compounding.*

Impulse-reaction turbines. Parsons' turbine. Fig. 100 shows a longitudinal section through a turbine constructed by Messrs. C. A. Parsons & Co., Ltd., for a South African power station. This turbine runs at 3000 r.p.m., developing 20,000 kW. (26,800 H.P.) in a single cylinder. Steam (150,000 lb. per hour) is supplied at a pressure of 400 lb. per sq. in. (gauge) at the stop valve, temperature 725° F. (280° of superheat). The pressure drops gradually to a condenser vacuum of 28·8 in. At its most economical output, which is 80% of full load, the turbine has a brake thermal efficiency of 31%. The absolute velocity of the steam at discharge is 620 ft. per sec.

The Parsons' turbine is called an impulse-reaction turbine, because the blading is of the converging type, and steam expands and generates kinetic energy, both in the fixed and moving blades. In other words, both the fixed and moving blades act as nozzles. Fixed blading carried by the stator or casing has an efficiency nearly equal to that of a good nozzle, and the steam is directed smoothly on to the moving blades carried by the rotor. The turbine is thus partly driven by the reaction of the steam leaving the moving vanes and giving a backward thrust as it passes from one set of fixed blades to the next. The moving blades may be likened to a machine-gun, which has to take the recoil in sending out a stream of bullets. By

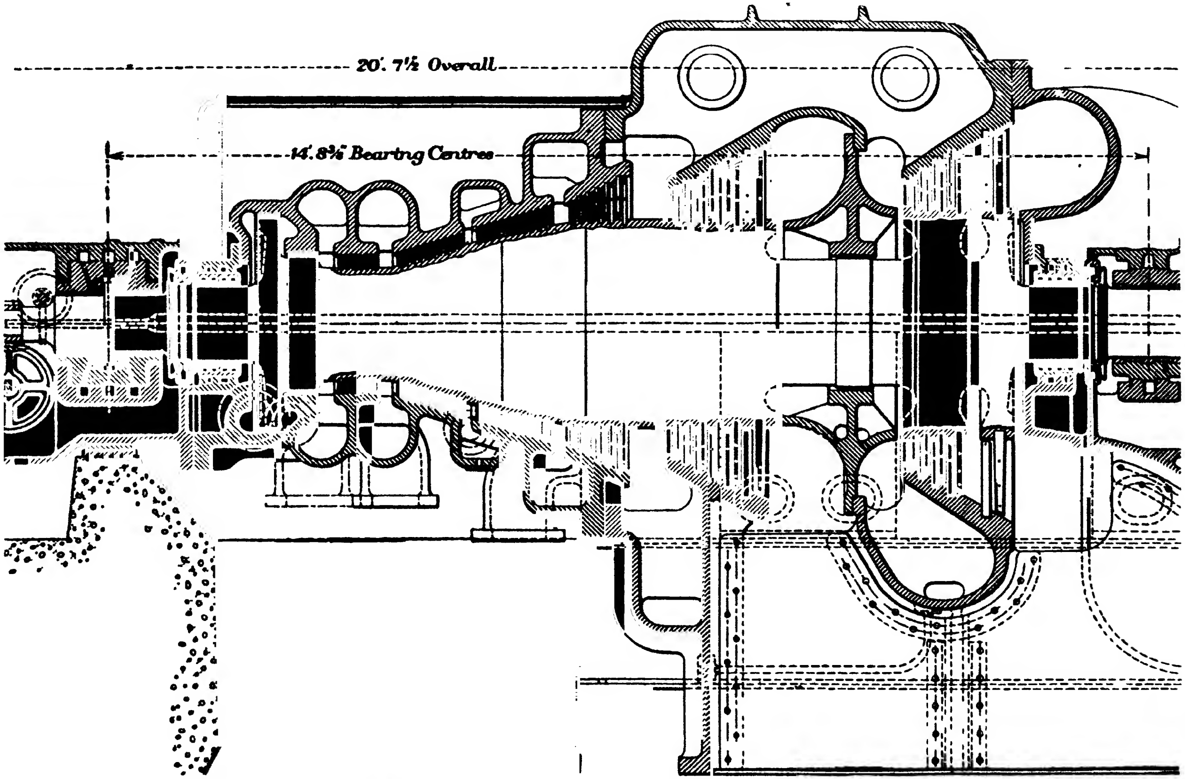


FIG. 100. Longitudinal section through a Parsons' steam turbine. By courtesy of *Engineering*.

having a large number of stages on one rotor and stator, each stage consisting of a ring of moving and fixed blades, and by exhausting the steam from one stage to the next, a smaller amount of energy is abstracted at each stage. The energy of the steam can be absorbed gradually, and there is less waste of steam, and lower speeds are possible without loss of efficiency. This principle, whereby the total pressure drop is accomplished in stages, is referred to as *pressure compounding.*

The turbine rotor is a single forging supported in bearings 14 ft. $8\frac{3}{8}$ in. apart, and has a maximum diameter of 40 in. To ensure soundness it has been bored axially from end to end to permit of internal examination. The left-hand or high-pressure end of the rotor carries 33 rows of moving blades gradually increasing in height. The first 6 rows of blades are mounted on a cylindrical portion of the rotor and have a height of $1\frac{3}{16}$ in. These are by-passed at full output and the steam passes direct to the next 21 rows, mounted on a conical portion of the rotor, the blades ranging in height from $1\frac{1}{4}$ in. to $2\frac{3}{8}$ in. When the steam has passed through these stages it has a pressure of about 35 lb. per sq. in. absolute, and some of it is tapped off or " bled " for heating boiler feed water. More steam (at $6\frac{1}{2}$ lb. per sq. in. absolute) is also abstracted for the same purpose at the end of the high-pressure section, thus giving more room for the expansion of the remaining steam. About 21,000 lb. of steam are bled from the turbine per hour. The double-flow low-pressure portion of the turbine consists of two parts, 6 stages on the left-hand and 5 on the right-hand portion. At the tips of the largest blades, which are $13\frac{1}{2}$ in. in height, the speed is 877 ft. per sec. Fig. 101 shows some rotor blading placed in position.

After leaving the high-pressure portion of the turbine, the steam divides into two parts, half going through the left-hand portion of the low-pressure turbine and half through the right-hand portion, before being exhausted to the condenser. The blades and steam passages have to be increased in size as the steam flows through the turbine. This is because the steam is expanding, that is, dropping in pressure and increasing in volume. Owing to the slight difference of pressure on the two sides of a row of blades, there is a small force which tends to make the steam leak past the tips of the blades

without doing useful work. Careful construction is necessary to reduce leakage to a minimum, as packing of any kind is impossible owing to the heat generated and its destructive effect on any packing material. Leakage is greatly reduced by using fine working clear-

FIG. 101. Turbine blading. By courtesy of *Engineering*.

ances, preferably axial and not radial, and by thinning edges which may come into contact, so that little harm can be done to the blading.

Figs. 102 and 103 show how the blades are fitted and how leakage is lessened. The tips of the blades are riveted to the end tightening strips, while the roots and spacers are welded and provided with serrations to fit those on the rotor and stator grooves. A is a fixed stator blade, and its end tightening strip has a forked or double feather edge, the lower edge almost making contact with the

roots of the adjoining moving blades, while the upper edge guides the steam smoothly on to the latter with only slight leakage. The shrouding on the moving blade B has a feather edge almost touching the root of the adjacent fixed blade. This lessens leakage over the tips of the moving blades. At the high-pressure end of this turbine the blading is made of specially treated and brazed stainless iron.

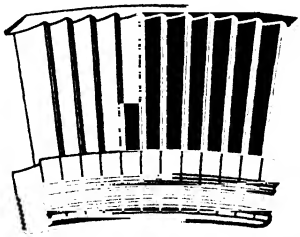


FIG. 102. Method of attaching blades to rotor.
By courtesy of *Engineering*.

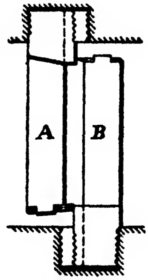


FIG. 103. Method of preventing leakage.
By courtesy of *Engineering*.

Low-pressure blading is often made of brass, and the high-pressure blading of steel in order to withstand the action of superheated and high-pressure steam.

To prevent leakage at the shaft ends carbon glands are employed, while between the two low-pressure portions of the turbine the serrations (see Fig. 104) lessen leakage because they provide a tortuous path and tend to set up eddy flow. As the steam flows from left to right it sets up a thrust in that direction, and this is balanced by two dummy flanges near the high-pressure blading and by a double Mitchell thrust block situated in the left-hand bearing. The thrust block allows thrust in either direction to be met, and registers accurately the position of the rotor in the casing. Provision is also made for a fine axial adjustment of the rotor.

Forced lubrication is made by pump to all bearings. Governing is achieved by relay through motors to double-beat balanced valves.

Intermediate bearings, which form a necessary and undesirable feature of the Rateau and Curtis turbines, are not required for a Parsons' turbine.

Fig. 104. Parsons' turbine under construction, showing blading and bottom half of stator. By courtesy of *Engineering*.

Advantages of turbines over reciprocating engines. (1) Less attention is required during running, and repair costs are generally less. (2) The propelling force is applied directly to the element being propelled, and not through a crank and connecting rod. (3) Less oil is required for lubrication, and none finds its way into the exhaust steam and boiler feed water. (4) Lighter foundations can be used owing to the absence of vibrations. (5) The applied torque is more uniform to the driven shaft. (6) All the moving parts are enclosed, and there is less danger of entanglement and accident. (7) There is less frictional loss due to fewer sliding parts. (8) Large powers, due to the high rotational speed, are readily incorporated in one comparatively small compact unit. This high speed is suitable for electrical power generation. (9) The benefit of the full expansion of the steam to its limit is possible with high vacuum, as the condenser can be brought close up to the low-pressure exit of the turbine, and the turbine is very efficient at low pressures. (10) Steam consumption is less. (11) The turbine, being almost perfectly balanced, is nearly vibrationless, and it is difficult to attain this state of affairs with reciprocating engines. (12) As the turbine stages form a convenient series of steps or pressure gradient, steam can be bled at any pressure for heating feed water or for industrial purposes. (13) The turbine can take an overload with little loss of efficiency.

Disadvantages. (1) Turbines must be run at high speeds, and this is not always desirable in the driven machine. Reduction gearing of an efficient and quiet type has largely overcome this disadvantage. (2) The blading is easily damaged, especially when raising the top half of the stator for repairs. (3) For high efficiency the turbine needs a high vacuum and very efficient condenser. (4) Leakage at high pressures is difficult to prevent.

It is claimed that a steel alloy containing chromium, nickel, aluminium and titanium, which resists oxidation in air and steam at 900° C., will prove very useful in the construction of turbine blading subjected to highly superheated steam.

Energy aspect of heat losses and heat drop. When a quantity of steam loses heat, this heat must either be wasted in the form of leakage, radiation or conduction, or it is converted into useful mechanical work. This mechanical work, in the particular case of a

turbine, is evident in the form of kinetic energy possessed by the steam jet upon impact on the vanes; so that some portion of the heat content of the admitted steam is converted to velocity, or kinetic energy, in the jet.

The loss of heat content between admission and exhaust is known as the **heat drop**, and may be calculated from the difference between the total heat of 1 lb. of steam at admission and that of 1 lb. of steam at exhaust. The velocity of the jet V may then be theoretically assessed, if this heat drop be converted from heat to mechanical energy and the result equated to the kinetic energy due to the velocity; so that **heat drop** $=\frac{WV^2}{2g}$, where W is 1 lb. if the heat drop of 1 lb. of steam is considered. (See energy equations, p. 211.)

Example 1. *Dry steam enters the nozzles of a de Laval turbine at a pressure of* 200 *lb. per sq. in. (absolute), and leaves at a pressure of* 4 *lb. per sq. in. with a dryness fraction of* 0·837. *Find the heat drop or heat energy available per lb. of steam. Also find the theoretical velocity of the steam entering the blades, and if the exit velocity is* 1510 *ft. per sec., find the efficiency of the blading. At what pressure is steam exhausted from the turbine? Assume the nozzle is frictionless.*

Heat in 1 lb. of dry saturated steam at 200 lb. per sq. in.
$=669{\cdot}69$ C.H.U.

Heat in 1 lb. of steam at 5 lb. per sq. in.
$=0{\cdot}837\times558{\cdot}28+67{\cdot}1=534{\cdot}38$ C.H.U.

Heat drop by difference $=$ **135·31 C.H.U.**

Work available $=$ heat drop $\times J=$ kinetic energy of steam

$$=\frac{WV^2}{2g}, \text{ where } W=1 \text{ lb.}$$

Therefore $V^2=2g\times J\times\text{heat drop }(H)$,

or $V=\sqrt{2\,.\,g\,.\,J\,.\,H}$

$$=\sqrt{2\times32{\cdot}2\times1400\times135{\cdot}31}=3492.$$

Theoretical velocity $=$ **3492 ft. per sec.**

Energy loss per lb. in passing through blades $=\frac{3492^2}{2g}-\frac{1510^2}{2g}$.

$$\therefore\ \text{Efficiency}=\left(\frac{3492^2}{2g}-\frac{1510^2}{2g}\right)\div\frac{3492^2}{2g}=81{\cdot}3\%.$$

The steam is exhausted at 4 lb. per sq. in. since the pressure on both sides of the impulse blading is the same.

Example 2. *The steam pressure for the Parsons' turbine described in this chapter drops from 400 lb. per sq. in. gauge and 725° F. to a vacuum of 28·8 in. Calculate the amount of heat energy supplied to the turbine per lb. of steam. Assume the exhaust steam is 82·3% dry, and the specific heat of superheated steam as 0·62. What is the heat drop?*

From tables, total heat of dry saturated steam at 400 lb. per sq. in. at a temp. of 444·7° F. = 1212·3 B.Th.U.

Total heat of above steam at 725° F. $= 1212 \cdot 3 + 0 \cdot 62\,(725 - 444 \cdot 7)$
$= 1386$ **B.Th.U. per lb.**

28·8 in. of vacuum = 1·2 in. of mercury absolute.

Pressure in lb. per sq. in. = wt. of mercury (density 0·49 lb. per cu. in.) which is standing on 1 sq. in.

$$= 1 \times 1 \times 1 \cdot 2 \times 0 \cdot 49 = 1 \cdot 2 \times 0 \cdot 49$$
$$= 0 \cdot 588 \text{ lb. per sq. in.}$$

Total heat (from tables) at 0·588 lb. per sq. in. and dryness 82·3%

$$= 52 \cdot 42 + 0 \cdot 823 \times 1041 \cdot 84 = 908 \cdot 5 \text{ B.Th.U.}$$

Heat drop = 1386 − 908·5 = **477·5 B.Th.U.**

Example 3. 2·5 *lb. of steam initially at* 300 *lb. per sq. in. abs. and* 200 *Cen. degrees of superheat is expanded in a nozzle to* 80 *lb. sq. in. abs. and* 20 *Cen. degrees of superheat. Calculate the change in heat value or heat drop per lb. and the speed of the steam at the outlet from the nozzle. Assuming the whole of the energy converted to mechanical work, what is the power available?*

Total heat in 1 lb. of steam at 300 lb. per sq. in. abs. and 200 Cen. degrees of superheat (from tables) = 784·6 C.H.U.

Total heat in 1 lb. of steam at 80 lb. per sq. in. abs. and 20 Cen. degrees of superheat (from tables) = 669·8 C.H.U.

∴ Heat drop per lb. = (784·6 − 669·8) or **114·8 C.H.U.**

Energy equivalent in ft. lb. = 114·8 × 1400 = 160,720
= kinetic energy of steam if losses are neglected.

$$\therefore \frac{WV^2}{2g} = 160{,}720 \text{ where } W = 1 \text{ lb.}$$

$$\therefore V = \sqrt{160{,}720 \times 64 \cdot 4}$$
$$= \mathbf{3216 \text{ ft per sec.}}$$

Power available with 2½ lb. of steam per min.

$$= 2\tfrac{1}{2} \times 160{,}720 \text{ ft. lb. per min.}$$

$$\therefore \text{H.P.} = \frac{2\frac{1}{2} \times 160{,}720}{33{,}000} = 12 \cdot 17.$$

Example 4. *If 24,000 lb. of steam per hour enters a turbine at a pressure of 250 lb. per sq. in. abs. and 80 Fahr. degrees of superheat and exhausts at 1 lb. per sq. in. abs. and 0·95 dry, determine*

(1) *the heat drop or change in heat value per lb. of steam,*

(2) *the change of volume per lb. of steam,*

(3) *the horse power developed, assuming no losses.*

Use the approximate form of Callendar's equation for superheated steam.

(1) From steam tables, total heat at 250 lb. per sq. in. abs. and 80 Fahr. degrees of superheat $= 1255{\cdot}7$ B.Th.U. per lb.

Total heat at 1 lb. per sq. in. abs. and 0·95 dry

$$= 69{\cdot}5 + 0{\cdot}95 \times 1032{\cdot}9$$
$$= 1050{\cdot}8 \text{ B.Th.U. per lb.}$$

$\therefore$ Change in heat value $= 1255{\cdot}7 - 1050{\cdot}8$ or **204·9 B.Th.U. per lb.**

(2) $$V = \frac{1{\cdot}2464}{P}(H - 835) = \frac{1{\cdot}2464}{250}(1255{\cdot}7 - 835)$$
$$= 2{\cdot}097 \text{ cu. ft.} = \text{initial volume.}$$

Final volume per lb. $= 0{\cdot}95 \times$ specific volume at 1 lb. per sq. in. abs.

$$= 0{\cdot}95 \times 333{\cdot}1 \text{ or } 316{\cdot}4 \text{ cu. ft.}$$

$\therefore$ Increase in volume $= 316{\cdot}4 - 2{\cdot}097$ or **314·3 cu. ft./lb.**

(3) Heat energy drop per lb. $= 204{\cdot}9$ B.Th.U.

" " " min. $= 204{\cdot}9 \times 24{,}000 \div 60$ B.Th.U.

$$= 81{,}960 \text{ B.Th.U.}$$

$$\therefore \text{Horse power available} = \frac{81{,}960 \times 778}{33{,}000} = 1932{\cdot}3.$$

EXERCISES ON CHAPTER IV

The steam engine and its control.

1. Enumerate the chief parts of a simple non-condensing double-acting steam engine, and briefly state their chief functions.

2. Sketch and describe a slide valve, and show how it is worked and how it distributes the steam.

3. Define the terms : steam or outside lap, exhaust or inside lap, angle of advance and travel in relation to the simple D slide valve.

4. Make an outline sketch of an eccentric and explain briefly how it operates the slide valve of a simple engine.

5. The area of a slide valve is 80 sq. in. and the steam pressure on it is 150 lb. per sq. in. Find the force required to move it. Coefficient of friction between valve and chest $= 0{\cdot}1$.

6. Describe methods employed for automatically controlling and steadying the speed of a simple steam engine.

7. Describe with sketches one form of governor for a steam engine.

8. Explain the benefits to be derived from employing the expansive properties of steam. How can it be arranged ?

9. What means have been employed in modern engines to reduce condensation losses in cylinders ? Why is it undesirable to employ the same passages for boiler and exhaust steam ?

10. Describe the chief features of the Uniflow engine, and state its advantages over other types of reciprocating engines.

11. The boiler of a steamship supplies steam at 220 lb. per sq. in. abs. and at 775° F. to a heat exchanger, in which its temperature drops to 590° F., before supplying the steam to the high pressure cylinder. Find the number of B.Th.U. supplied by the boiler steam per lb. to the exhaust steam from the high pressure cylinder in this heat exchanger. Neglect losses and take the specific heat of superheated steam at this pressure as 0·56.

12. The cylinders of a compound engine are 30 in. and 64 in. in dia. respectively. Cut-off in the H.P. cylinder occurs at $\frac{1}{2}$ stroke. What is the ratio of expansion for the engine ?

13. A triple expansion engine has cylinders 20 in., 35 in., and 48 in. in diameter. If the high-pressure valve cuts off at $\frac{3}{8}$ of the stroke, what is the total ratio of expansion employed by the engine ?

14. The steam pressure on a piston of 4 in. diameter is 200 lb. per sq. in. and the back pressure is $6\frac{1}{2}$ lb. per sq. in. Find the resultant force on the piston. If the steam is cut off at $\frac{1}{3}$ stroke, find the ratio of expansion and the hypothetical mean effective pressure, neglecting clearance.

15. If steam be admitted into the cylinder of a steam engine at a pressure of 75 lb. per sq. in. above that of the atmosphere (which may be taken to be 15 lb. per sq. in.) and be cut-off at one-third of the stroke, calculate the pressures at $\frac{1}{2}$, $\frac{3}{4}$ and at the end of the stroke. Assume $PV = \text{const.}$

Draw to scale a diagram which shows how the pressure varies during the stroke. (U.L.C.I.)

16. A steamship with triple expansion engines and exhaust turbines and using steam at 220 lb. per sq. in. abs. and 200 Fahr. degrees of superheat has cylinders 22 in., 37 in. and 61 in. in diameter with a common stroke of 45 in. Assuming no cut-off in the H.P. cylinder, calculate the total ratio of expansion. Using this ratio of expansion and taking the expansion as being according to the law $PV^{1 \cdot 15} = \text{const.}$, estimate the steam pressure at exhaust from the reciprocating engines and thus at entry into the turbine. Neglect losses and the effect of clearance space.

17. The length of the connecting rod of a locomotive is four times the length of the crank. Find by a scale drawing (*a*) the position of the crank when the piston is at quarter and half stroke, (*b*) the position of the piston when the crank is 90° from a dead point.

18. If the angle of advance of an eccentric is 30° and its throw is $3\frac{1}{2}$ in., find by a scale drawing the distance of the valve from its mean position when (*a*) the crank is at its inner dead centre, (*b*) when the crank has turned through another 30°.

19. Draw a sectional scale view of a D slide valve from the following information: Outside lap $=\frac{3}{4}$ in. Inside lap $=\frac{1}{4}$ in. Breadth of steam port $=1$ in. Breadth of exhaust port $=3\frac{1}{2}$ in. Thickness of metal between ports $=1$ in. Travel $=3\frac{1}{2}$ in.

20. Find the width of opening of the steam port for the valve in Question 19 for the two positions of the crank in Question 18.

21. Given that the eccentricity of an eccentric is $2\frac{3}{4}$ in., the steam lap of a D slide valve $1\frac{1}{8}$ in. and the lead given to the valve by the eccentric as $\frac{1}{8}$ in., determine

(*a*) the travel of the slide valve,
(*b*) the angle of advance of the eccentric.

22. For the valve and eccentric as given in Question 21, and assuming no inside or exhaust lap, find the positions of the crank relative to the centre line of the piston for the events of admission, cut-off, release and cushioning.

23. Answer Question 22, but assume an inside or exhaust lap of $\frac{1}{2}$ in.

24. Given that a simple slide valve has a travel of $6\frac{3}{4}$ in., outside or steam lap $1\frac{5}{8}$ in., inside lap $\frac{3}{8}$ in. and lead $\frac{3}{16}$ in., obtain the relative crank and piston positions for the events of admission, cut-off, release and compression. Express the piston positions as fractions of the completed stroke. Find the angle of advance.

25. Construct a probable indicator diagram for the valve control specified in Question 24.

26. Describe a Stephenson's link motion and make an outline sketch. Explain how the engine may be reversed.

Steam engines, power, performance and testing.

27. Sketch and describe a steam engine indicator. Why is it used ?

28. For the indicator reducing gear shown in Fig. 92, and taking AB $=12{\cdot}8$ in., AD $=3$ in., BC $=1{\cdot}8$ in. and a piston stroke of 8 in., find by a scale drawing the actual travel of the drum and the position at one quarter and three quarter stroke of the piston. Take the drum as being at mid-travel when AB is vertical.

29. Calculate the stiffness of spring required to give an indicator scale of 100 lb. per sq. in. per in. for an indicator piston area of $0{\cdot}75$ sq. in. and a ratio of pencil travel to indicator piston travel of 6 to 1.

30. Sketch the type of indicator diagram usually obtained from a steam engine, pointing out the most important features.

31. Show by sketches the probable effect of the following upon the indicator diagram for a steam engine with correct valve setting; (*a*) too great a ratio of expansion, (*b*) too late release, (*c*) insufficient lead to valve, (*d*) too early release, (*e*) too early compression or cushioning.

32. Describe the method of obtaining the indicated horse power of a single-acting engine. What additional measurements and calculations are necessary if the engine is double-acting?

33. The high-pressure cylinder of a high-pressure compound locomotive has a bore of 11·4 in. and a stroke of 25 in. The lengths of the mid-ordinates in inches taken from a typical indicator diagram are as follow: 0·72, 1·025, 1·025, 0·78, 0·54, 0·4, 0·28, 0·19, 0·1, 0·07.

Calculate the indicated horse power developed in this cylinder if the crank shaft revolves at 232 r.p.m. The scale of the indicator spring used was 1/400. Steam is admitted to both sides of the piston.

34. A double-acting steam engine has a cylinder diameter of 6 in. and a stroke of 10 in. The mean effective pressure of the steam is 45 lb. per sq. in. Determine the engine speed and the mean piston speed if 21 H.P. is to be developed in the cylinder.

35. The mean effective pressure of the steam in an engine cylinder is 50 lb. per sq. in. The cylinder diameter is 16 in. and the piston stroke 22 in. Find the speed of the engine in r.p.m. when the horse power is 170. (U.L.C.I.)

36. Indicator diagrams taken from each end of the cylinder of a Uniflow steam engine of cylinder diameter 39 in. and stroke 56 in. are shown in Fig. 105. The piston and tail rods are 6 in. in diameter. Calculate the I.H.P. at 130 rev. per min.

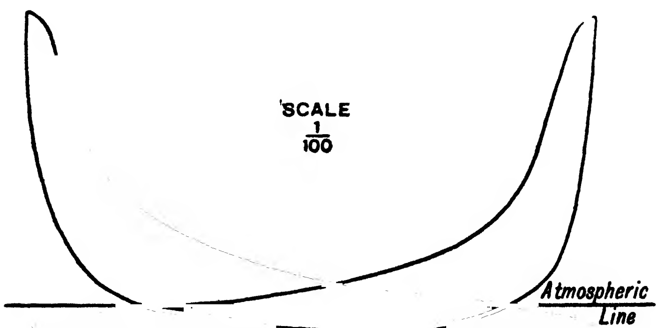


Fig. 105. Indicator diagram from Uniflow steam engine.

37. Fig. 106 shows indicator cards taken from the high-pressure cylinder of an L.M.S. compound locomotive with cut-off at 0·67 stroke. The cylinder is 19 in. in diameter and the stroke 26 in., while the piston and tail rods are $3\frac{1}{2}$ in. in diameter. Calculate the indicated horse power, if the locomotive speed was 50·8 m.p.h. and the driving wheels 6 ft. 9 in. in diameter.

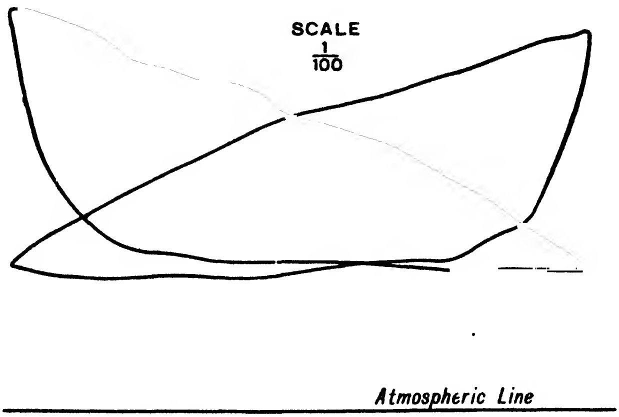


FIG. 106. Indicator diagram from high-pressure cylinder of a locomotive.

38. The following data is taken from a test on a 3-cylinder German State Railway high-pressure compound locomotive with two L.P. cylinders. Speed 55 m.p.h. Diameter of driving wheels, 6 ft. 6 in. Cut-off in each cylinder 35%.

Each L.P. cylinder 19·7 in. diameter, 24·8 in. stroke, M.E.P. 53·4 lb. per sq. in.

H.P. „ 11·42 in., diameter 24·8 in., stroke, M.E.P. 170·5 lb. per sq. in.

Calculate the horse power developed in each cylinder, and hence determine the total indicated horse power.

39. Sketch and describe a form of rope brake suitable for testing an engine of about 12 H.P. Show the arrangements made for cooling the brake.

40. If in an engine test the net load at the end of a brake arm of 27 in. is 250 lb., calculate the indicated horse power if the speed averaged 120 r.p.m. Also calculate the indicated horse power if the mechanical efficiency is 75%.

41. Distinguish between a transmission and an absorption dynamometer, and describe a form of one of them.

42. The following data were obtained during an experiment with a double-acting single cylinder steam engine: mean effective steam pressure, 30 lb. per sq. in.; number of revolutions per min., 180; effective force at brake drum circumference, 160 lb. The diameter of the cylinder was 8 in., piston stroke 10 in., and the brake drum diameter 4 ft. Find the I.H.P., B.H.P., and mechanical efficiency of the engine. (U.L.C.I.)

43. A steam engine develops 52 I.H.P. and uses 2100 lb. of dry steam per hour at 70 lb. per sq. in. abs. The exhaust pressure is 4 lb. per sq. in. and dryness fraction 0·7. Calculate

(*a*) the rate at which heat is being supplied to the cylinder,
(*b*) the heat equivalent of the I.H.P.,
(*c*) the indicated thermal efficiency of the engine.

44. State the observations you would make in conducting a test on a single cylinder double-acting steam engine.

45. A compound locomotive using 17 lb. of steam per indicated horse power per hour at 215 lb. per sq. in abs. and superheated to 650° F., exhausts the steam at 20 lb. per sq. in. abs. and with dryness fraction 0·97. Calculate the indicated thermal efficiency (without boiler) and the heat rejected per I.H.P. hour. c_p for superheated steam 0·568.

46. A locomotive travelling at 56·3 m.p.h. has driving wheels 78·8 in. in diameter. The indicated horse power developed was 1143, using coal of calorific value 13,700 B.Th.U. per lb. at the rate of 60 6 lb. per sq. ft. of grate area per hour. If the draw bar pull was 6,422 lb. and the grate area 20 sq. ft., calculate

(*a*) the crank shaft speed in r.p.m.,
(*b*) the brake or draw bar horse power,
(*c*) the mechanical efficiency,
(*d*) the overall brake and indicated thermal efficiencies.

47. Steam at an absolute pressure of 90 lb. per sq. in. is admitted to a cylinder and cut-off at 0·4 stroke. Draw the hypothetical indicator diagram to scale and find the area of the diagram and the theoretical mean effective pressure of the steam during the stroke if the back pressure is 16 lb. per sq. in. Check your answer by using the formula for hypothetical mean effective pressure.

48. What mean effective pressure would be necessary if 16 H.P. is to be developed in a cylinder 10 in. in diameter and a stroke of 15 in. if the engine speed were 120 r.p.m.? The engine is single-acting.

49. From the data given below, (*a*) draw the hypothetical indicator diagram and determine its area, (*b*) find the theoretical mean effective pressure, and (*c*) calculate the indicated horse power, assuming a diagram factor of 0·75 and the engine single-acting:

Boiler pressure, 120 lb. per sq. in. abs. Rev. per min., 200. Cut-off, 0·4 stroke. Piston area, 20 sq. in. Stroke, 22 in. Back pressure, 9 lb. per sq. in.

50. Steam at 75 lb. per sq. in. abs. is admitted to a cylinder of a double-acting engine with a piston and tail rod. Taking cut-off as being at $\frac{1}{3}$ stroke and a back pressure of 4 lb. per sq. in. obtain the mean effective pressure. If the piston area is 120 sq. in. and the crank $10\frac{1}{2}$ in. long, calculate the theoretical work done per stroke in the cylinder.

51. Calculate the theoretical steam consumption for the engine in Question 50 neglecting condensation and the effect of clearance space for a speed of 150 r.p.m. if the specific volume of steam at 75 lb. per. sq. in. abs. is 5·805 cu. ft. per lb.

Also determine the work done per cubic foot of steam and compare your answer with the work done per cu. ft. of steam if steam is admitted at the full pressure of 75 lb. per sq. in. abs. throughout the stroke, *i.e.* without expansion.

52. The hypothetical mean effective pressure for a proposed engine is 66 lb. per sq. in. Taking a diagram factor of 0·7, find the dimensions for the bore and stroke of a single cylinder double-acting engine to develop 50 H.P. at 135 r.p.m. with a ratio of stroke to bore of 1·5.

53. Calculate the diagram factor for a locomotive engine cylinder in which steam is admitted at 172 lb. per sq. in. abs., the cut-off is at quarter stroke and the back pressure 23 lb. per sq. in. From a diagram the actual mean effective pressure was found to be 55·73 lb. per sq. in.

54. The following observations were made when making a test on a locomotive :

I.H.P., 1190; steam consumption, 19,380 lb. per hour, of which 1200 lb. was used for train heating and auxiliaries; boiler pressure, 250 lb. per sq. in. abs. and 250 Fahr. degrees of superheat; exhaust pressure, 19 lb. per sq. in. abs. and dryness fraction 0·97; coal consumption, 73·9 lb. per sq. ft. of grate per hour; calorific value of coal, 14,050 B.Th.U. per lb.; grate area, 31 sq. ft.; crank shaft speed, 212 r.p.m.

Calculate :

(*a*) the cylinder steam consumption per horse power per hour,
(*b*) the heat received by the cylinders per minute above 32° F.
(*c*) the heat equivalent of the indicated horse power,
(*d*) the thermal efficiency of the engines,
(*e*) the heat lost to exhaust per minute,
(*f*) the thermal efficiency of the locomotive on the I.H.P. basis.

55. A small high-pressure compound locomotive developing a draw bar horse power of 800 consumed 1800 lb. of coal per hour of a calorific value of 13,500 B.Th.U. per lb., and used 12,000 lb. of steam per hour initially at 850 lb. per sq. in., and superheated so that the total heat per lb. was 1400 B.Th.U. The feed water temperature was 52° F. Calculate (*a*) the thermal efficiency of the boiler, and (*b*) the brake or draw bar thermal efficiency of the engine and boiler.

56. Fig. 107 shows indicator diagrams taken from a stationary compound engine. The engine particulars are :

H.P. or high-pressure piston area, 58·6 sq. in.

L.P. or low-pressure piston area, 192·3 sq. in.

Stroke 22 in. in each case.

Mean steam pressure at stop valve is 69·45 lb. per sq. in. abs. and condition is dry.

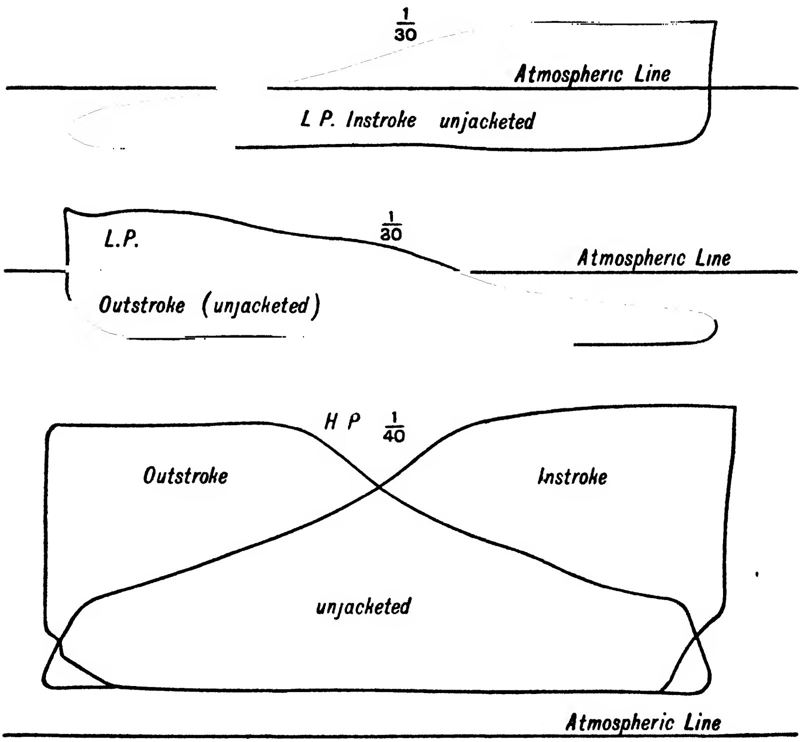


FIG. 107. Indicator diagrams from compound steam engine.

Revolutions made, 9865 in 100 min. test.

Mean torque or turning moment on brake wheel, 2318·8 lb. ft.

Wt. of steam supplied, 2013 lb. in 100 min.

Total heat supplied per lb. of steam, 594·2 C.H.U.

Find (*a*) the mean effective pressure and horse power for the H.P. and L.P. cylinders. (*b*) total I.H.P. (*c*) B.H.P. and mechanical efficiency. (*d*) steam per B.H.P. hour. (*e*) brake thermal efficiency.

57. What is the nature of the relation existing between the steam consumption for an engine and the power developed, assuming constant cut-off, if the engine is of the reciprocating type? How does the use of superheated steam affect the relation?

58. The results obtained by testing an engine under different loads are shown in the table :

Steam consumption in lb. per hour (S)	437·5	462	529	611
I.H.P. (P) - - - - - -	10·1	15·2	19·8	25·4

Plot a graph and obtain an approximate linear relation between S and P. What is the probable steam consumption for a power of 18 H.P.? Also find the rate of steam consumption per I.H.P. hour when the power developed is 20.

Steam turbines.

59. Briefly describe a de Laval turbine, and show how the energy in the steam is converted into kinetic energy.

60. Dry saturated steam at 180 lb. per sq. in. abs. is supplied to a de Laval turbine, and it is exhausted at atmospheric pressure, 14·7 lb. per sq. in. absolute, with a dryness fraction of 0·865. Find the heat drop and the steam speed as it leaves the nozzles, if friction and all losses are neglected. What is the blade efficiency if the steam leaves the blades with an absolute speed of 1500 ft. per sec. ?

61. Why must a de Laval turbine run at a higher speed than a Parsons' turbine ? What is the essential difference between an impulse turbine and an impulse-reaction turbine ?

62. Describe how the difficulties of leakage and axial thrust are overcome in a modern form of Parsons' turbine.

63. The Parsons' turbine described in this chapter is guaranteed to deliver 1 unit of electricity at the generator terminals for each 10,986 B.Th.U. supplied at the stop valve at its most economical output of 16,000 kW. What is the thermal efficiency of the turbine and generator for this output ?

If the output is 20,000 kW., then 11,185 B.Th.U. are required per kilowatt hour. What is the efficiency at this maximum load ?

64. 3 lb. of steam per minute, initially at 300 lb. per sq. in. and 180 Cen. degrees of superheat, is expanded in a nozzle to 80 lb. per sq. in. and 30 Cen. degrees of superheat. Calculate the heat drop per lb. and the steam speed at the outlet to the nozzle. Neglecting all energy loss, find the power available. Take c_p for superheated steam as 0·56 at the higher pressure and 0·54 at the lower pressure.

CHAPTER V

INTERNAL COMBUSTION ENGINES

Gas, heavy-oil and petrol engines—Engine operation, performance and testing

ALL engines which burn fuel within the working cylinder are included in the term **internal combustion engines.** These engines may be classified according to the type of fuel used, for example, gas, oil or petrol engines. The burning of the fuel in the engine cylinder provides a much more efficient heat engine theoretically, but the high temperatures and pressures involved cause constructional and operative difficulties which are not easy to surmount, especially with large power units.

Cycles of operation. Internal combustion engines may be also classified according to the cycle of operations employed, that is, to the arrangements made for carrying out the four fundamental processes of charging, firing, compression and exhaust. The most common cycles are (1) the four-stroke cycle which takes four strokes of the piston to perform the four operations, and (2) the single-acting two-stroke cycle which takes two strokes to perform the four operations.

The **four**-stroke **Otto cycle** was first advocated by Beau de Rochas in 1862, but was not put into practical effect until 1876 by Dr. Otto. This cycle is really a compromise between attempts to produce an engine of high thermal efficiency on the one hand and at the same time mechanical simplicity on the other. The cylinder is provided with clearance space which acts as a combustion chamber such that the compression ratio $=\dfrac{\text{stroke}+\text{clearance volume}}{\text{clearance volume}}=r$. In the Otto cycle a combustible mixture of fluid fuel and air is drawn into the cylinder during the suction stroke (see Fig. 108 (*a*)), at approximately a little less than atmospheric pressure. On the return stroke (Fig. 108 (*b*)) this charge is compressed and the pressure rises, its ultimate value depending upon r, which in turn depends upon the type of engine and the fuel used. At about the dead point, or perhaps a little before, the fuel is ignited and explosion or burning and expan-

sion occur (Fig. 108 (*c*)). As the mixture cannot expand instantaneously the rapid ignition causes a sudden rise of pressure, and the piston is driven forcibly forward while the pressure falls. During the fourth stroke the spent gases of combustion are driven from the cylinder (Fig. 108 (*d*)), through the exhaust valve. Thus the way is prepared for drawing in a new charge and a repetition of the cycle of operations. The cams used to raise the inlet and exhaust valves

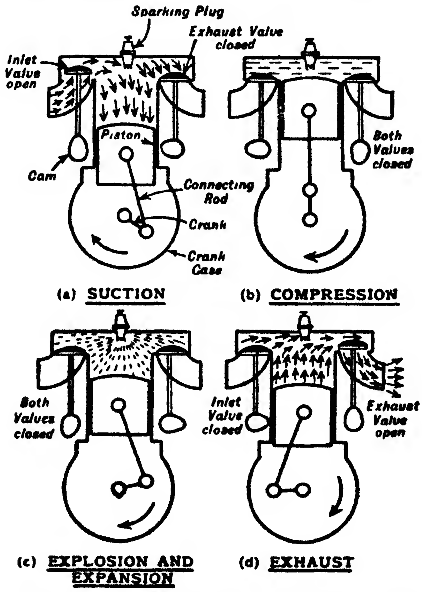


FIG. 108. The four-stroke or Otto cycle.

are turned by a shaft, called the cam or half-speed shaft, which is geared to the main crank shaft of the engine so that the cam shaft rotates at exactly half the crank shaft speed. This arrangement ensures that the inlet and exhaust valves are lifted once per two revolutions of the engine.

The gas engine. The parts of a small gas engine are shown in Fig. 109. As compared with the small reciprocating steam engine the chief differences are (1) the absence of a crosshead, (2) in the valve gear, (3) in the jacketing arrangements, and (4) in the use of

a trunk piston open at one end in the single-acting engine, and which takes the place of the combined piston and crosshead in the steam engine.

In the gas engine the connecting rod is directly coupled to a hollow cylindrical trunk piston of large bearing surface by means of a pin called a gudgeon pin ; the small end of the connecting rod oscillates about the gudgeon pin, which is fitted and fixed into bearings in the piston. To prevent the escape of gases the piston is fitted with rings similar to those used in the steam engine. Screw gears enable a cam shaft to be driven at half the speed of the crank shaft.

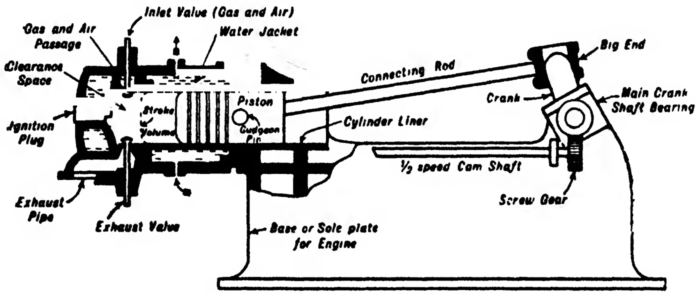


FIG. 109. Small gas engine.

Both inlet and outlet valves are kept closed and upon their seats by powerful springs, and they are lifted at the right time by levers actuated by cams on the cam shaft in a similar way to that illustrated in the heavy oil engine (Fig. 116). When the inlet valve opens, air and gas are drawn, by the outward motion of the piston and the suction set up, through non-return valves (not shown) into a passage and then through the inlet valve (Fig. 109). On the return stroke of the piston the mixture of gas and air is confined to the clearance space, and at the correct moment the mixture is ignited by an electric spark which is made to pass at this moment between the metal points of the ignition or sparking plug.

Since the temperature of combustion of the gas-air mixture is very great, the cylinder is prevented from getting red-hot by a surrounding water jacket through which water circulates, the circulation being set up and maintained by convection currents. In large cylinders developing more than 150 H.P. the pistons have also

to be cooled, and a pump circulates the cooling water. Contrast this with the steam jackets in the steam engine designed to prevent the cylinders cooling to such an extent as to cause excessive condensation of steam. With the internal combustion engine, between 30 and 40% of the heat energy of the fuel is carried away by jacket water, which means that this proportion of the fuel energy has to be deliberately sacrificed to put theory into practice. Modern materials of construction would soon lose their properties and strength unless their temperatures were controlled by cooling water or air.

Another desirable fitting for a gas engine is a gas bag, or **anti-fluctuator** as it is called. This helps to prevent, when town gas is being used, variations in the mixture during successive suction strokes, as it supplies a suitable reserve of gas near the engine. The anti-fluctuator consists of a cylindrical metal casing, with one of the circular metal faces replaced by a rubber diaphragm. To the centre of the diaphragm the spindle of the inlet valve to the anti-fluctuator is connected, so that when the diaphragm deflates it opens the valve and allows more gas to enter from the supply. The store of gas in the anti-fluctuator is always available for any sudden demand made by the engine. It is also necessary to fit some form of **silencer** to a gas or other internal combustion engine. The silencer usually fitted consists of a cast iron box having a capacity of about five times that of the engine cylinder. In this box the exhaust gases can expand freely, and baffles are provided to reduce their velocity before they are released into the atmosphere. As the gases expand and cool, moisture may be condensed inside the silencer, and some means must be provided for draining this off.

Since the gas engine working on the 4-stroke cycle receives only one impulse stroke per two revolutions, it is imperative to supply a larger flywheel than is necessary for a similar powered double-acting steam engine. This larger flywheel is needed to carry the engine past the dead points and to reduce the fluctuations in speed during the cycle of operations. Another advantage which the steam engine possesses is in the matter of starting. The double-acting steam engine or turbine can be made to start directly the steam stop valve is opened, whereas the internal combustion engine needs special starting equipment to set the engine in motion. One or two of the

methods of starting internal combustion engines are dealt with briefly in this chapter (p. 260).

Comparison of thermal efficiencies.

Type of heat engine	Gas engine	Heavy oil Diesel	Water-tube boiler and turbine
Fuel per B.H.P. per hour	19·3 cu. ft.	0·35 lb.	0·6 lb. oil
B.Th.U. supplied per B.H.P. per hour	9650	6685	11,400
Thermal efficiency (brake)	26·4%	38·35%	22·3%

The above table shows the relative oil fuel consumption and percentage of energy converted into useful work (thermal efficiency) for two types of internal combustion engine and for a water-tube boiler and turbine plant. The figures given for the latter are the record low fuel consumption for the power plant of a turbine steamer of 20,400 shaft horse power. It must be remembered, however, that there are other considerations besides thermal efficiency and fuel consumption in the choice of a heat engine, such as uniformity of speed and energy output, reliability, initial and maintenance costs, suitability for large or small outputs of power, and space available for installation. A brake thermal efficiency of 38·8% has been obtained from a high speed Diesel engine.

Expt. 34. **Valve mechanism for an I.C. engine.**

Objects. *To compare the amount of valve opening with the angle of rotation of the operating cam and the movement of the rocker bar.*

Apparatus. The apparatus for this experiment may be conveniently arranged on a horizontal board. The valve, valve guide, gas port and return spring and collar are fixed to operate freely as shown in Fig. 110. The end of the valve is faced to provide a smooth bearing surface for contact with a roller attached to an indicator, pivoted, and fitted with an extension spring. This indicator registers on a scale the valve displacement. The poppet end of the valve is operated by a rocker bar fitted with a roller at the cam end. The cam is free to rotate on its shaft and operate the rocker bar and thence the valve. An extension to the cam end of the rocker bar provides an indicator which shows on a scale the rocker bar

movement, or the radial variation of the cam. A scale behind the cam indicates the amount of cam rotation.

Method of procedure. Set the cam, by means of a square end key, so that the valve is closed, and notice that all the indicators register zero. Rotate the cam clockwise through 30°, and note (*a*) the rocker bar cam end movement and the valve displacement.

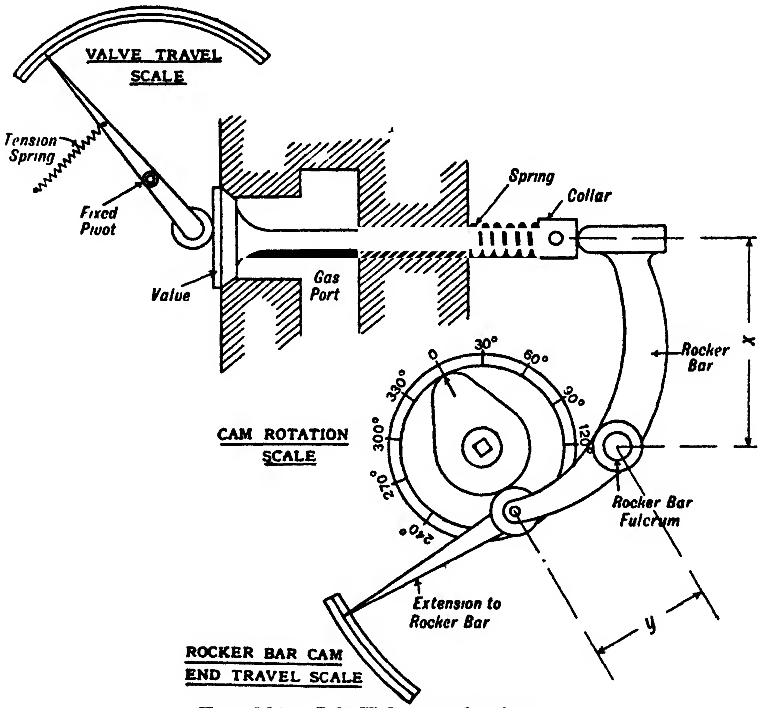


Fig. 110. I.C. Valve mechanism.

Continue the experiment, and obtain similar results for each 30° of cam rotation. Enter these results in a suitable table, and prepare a multiple axis graph of cam rotation in degrees against rocker bar movement and valve displacement. Calculate the velocity ratio of the rocker bar by measuring the distances x and y and finding the ratio $\frac{x}{y}$. Verify that the valve displacement is approximately given by $\frac{x}{y}$ times the rocker bar end displacement.

Conclusions. (*a*) Write down your observations concerning the amount of valve opening and its relation to the cam rotation.

(*b*) From your graph draw to a scale of three times full size the approximate cam profile for this valve gear, taking the minimum radius as $\frac{1}{2}$ inch.

Principles of action of the gas engine. Fuel. A mixture of gas and air is drawn into the cylinder, the proportion varying with the gas used. With coal gas about nine or ten times the volume of air is required, but poorer qualities of gas need less air. It is extremely important that the gas supply be uniform in quality, quantity, temperature and pressure, and clean, that is, free from tarry and gritty matter which would settle on valves and ignition plugs. The air supply is freed from dust by being drawn over some matting material, which also has the effect of reducing the noise set up by the suction of the engine. Greater power is obtained per stroke by ensuring that the explosive charge drawn into the cylinder is as cool, and therefore as heavy as possible. The gas and air supply should both be capable of adjustment, the gas by a gas cock or tap and the air supply by a butterfly valve (Fig. 64) or a rotary slide valve.

Suction. The outward motion of the piston creates a partial vacuum which causes a rush of air and gas into the cylinder, although the inertia of the gas and air and the resistance to flow through valves and pipes has to be overcome first. If the inlet valve is closed slightly late the inertia of the gases, now in motion, will cause the flow to continue right until the valve closes, and thus compensate somewhat for the lag at the commencement. It is also important that the exhaust valve should not close too early, otherwise more exhaust or spent gas is trapped in the cylinder, which prevents a full charge being drawn in during suction.

Compression. The mixture of gas and air is facilitated by the flow through the inlet valve and by the subsequent heat of compression. The ratio of compression depends upon the temperature attained during compression, which must not exceed the temperature of spontaneous ignition, and it is found that the more hydrogen there is present in the gas the lower must be the maximum permissible pressure. A common compression ratio is 5 or 4 : 1, and the equation of the compression curve is probably something like $pv^{1\frac{1}{3}}=\text{const.}$ A

leaky piston or other causes of loss will, of course, considerably reduce the final pressure.

Example. *If the pressure p_1 at the commencement of compression is atmospheric (14·7 lb. per sq. in.), find the pressure p_2 of the mixture at the end of compression if the compression ratio is 4 : 1.*

Now $p_2 v_2^{1\frac{1}{3}} = p_1 v_1^{1\frac{1}{3}}$ or $\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^{1\frac{1}{3}} = 4^{1\frac{1}{3}}$, since $\frac{v_1}{v_2} = 4$.

$$\text{Log}\,\frac{p_2}{p_1} = \frac{4}{3} \times \log 4 = \frac{4}{3} \times 0{\cdot}6021 = 0{\cdot}8028.$$

$$\therefore\ \frac{p_2}{p_1} = 6{\cdot}351 \text{ or } p_2 = 6{\cdot}351 \times 14{\cdot}7 = 93{\cdot}36.$$

$\therefore$ pressure = **93·36 lb. per sq. in.**

Explosion and Expansion. The charge is usually fired a little before the inner dead centre position, so as to ensure that the greatest pressure reached, which takes place a little time after ignition commences, may coincide with the momentarily stationary position of the piston. To determine the moment when ignition should occur, it will be necessary to consider the nature of the ignition, the nature of the mixture and the engine speed. **Pre-ignition**, or too early ignition, tends to reverse the direction of rotation as explosion occurs during compression, and so strains the materials and works against the engine. It may be due to (*a*) too great compression temperature and pressure, (*b*) faulty ignition gear, (*c*) red-hot particles of carbon or overheated portions of the cylinder walls or combustion chamber, (*d*) hot exhaust gases retained in pockets and on ledges in the combustion chamber, (*e*) overloading the engine, and so making it too hot.

When an explosion occurs on the suction stroke, that is, when the incoming fresh gases are ignited by gases still burning in the cylinder from the previous exhaust stroke, the engine is said to **back-fire.**

Exhaust. To allow the pressure in the cylinder to fall to that of the atmosphere by the end of the exhaust stroke, the exhaust valve is opened after about 75% of the working stroke is completed, the idea being to give ample time for the evacuation of exhaust gases from the cylinder. When separate air and gas valves are fitted, the air valve can be arranged to open just before the exhaust valve

closes, so that the air can help to sweep the exhaust gases from the cylinder. This action is termed **scavenging**, and since the gas valve is not opened until the exhaust closes there is no waste of fuel. The practice of placing the air inlet valve vertically over the exhaust valve in horizontal gas engines assists scavenging, as the air can sweep straight across and cool the combustion chamber and valves.

Control of engine speed or governing can be effected by :

(*a*) Cutting off the gas entirely and admitting air only when the speed exceeds a certain amount. (This is called the **hit and miss method of governing.**)

(*b*) Varying the opening of the gas inlet valve and keeping the air admission constant. This is called **quality governing.**

(*c*) Varying the quantity of mixture (but not the proportions) to the cylinder by giving a variable lift or opening to the inlet valve. This is called **quantity governing.**

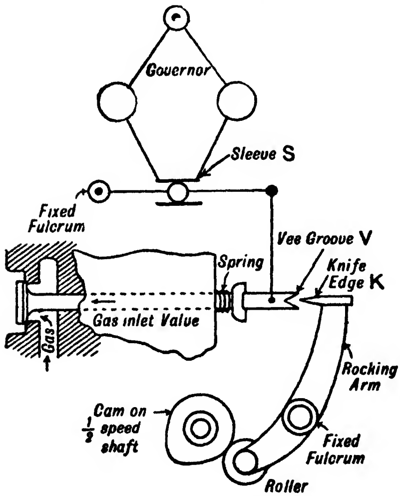


FIG. 111. Governing by the hit and miss method.

The principle of governing in the first method is shown diagrammatically in Fig. 111. At normal speed the cam on the half-speed shaft causes the rocker arm to oscillate at the correct time in the engine cycle, in such a way that the knife edge K engages with and moves the Vee grooved block V. The motion of the latter, which is in contact with the end of the spindle of the gas inlet valve, opens the valve against the compression of its closing spring and permits a charge of gas to enter the cylinder. Air enters by a separate valve (not shown) during the whole of the suction stroke. Should the engine speed increase, the governor raises the sleeve S, which lifts the block V and causes the knife edge K to miss, so that the gas valve is not opened. This naturally decreases the engine speed, and the block V

drops to its normal position. The cooling of the engine, due to the fact that a firing stroke is missed and only cold air is drawn into the cylinder, also tends to restore the engine to its normal running speed. In this method every charge is of normal strength, but the engine misses a charge intermittently, so that the output of the engine shall balance the usually constant external load on the engine, thus setting up the condition for steady speed. The hit and miss method is not suitable where large valves have to be operated and large valves controlled, but is economical in fuel consumption.

The second method of governing finds less favour, because altering the strength of the mixture should entail the altering of the point of ignition if the best results are to be achieved, which is an impracticable proposition. It is suitable for large engines with heavy pistons, since the compression pressure does not vary very much.

The third method is very suitable for large engines, as it does not tend to upset the engine efficiency; there is, however, owing to the variation in compression pressure, some difficulty in cushioning the reciprocating parts when these are heavy.

Self-contained gas engine plants. These consist of a gas generator and cleaner and a gas engine to convert the available chemical to mechanical energy.

A common form of plant generates **producer gas** by passing air and steam through red-hot carbonaceous matter. The idea employed is to burn carbon to form carbon monoxide, and to utilise as much as possible of the heat generated by the burning carbon in splitting up the steam into hydrogen and oxygen, of which the latter combines with more carbon to form carbon dioxide and carbon monoxide. Hence producer gas consists of hydrogen, carbon monoxide, carbon dioxide and nitrogen. Before passing to the engine, the gas is cooled and cleaned by flowing through a coke scrubber, which is kept sprinkled with water so that dust and many of the other impurities are removed. Producer gas requires a *minimum* of 1·1 cu. ft. of air per cu. ft. for complete combustion as compared with 5·25 cu. ft. of air per cu. ft. of town gas.

Engines using waste gases. In certain industries waste gases are available for utilisation as fuel, and when surplus gas cannot be sold, the gas engine forms the most economical means of converting heat

into mechanical or electrical energy. **Coke oven gas**, which is a by-product in the production of coke, is a very suitable fuel, as it contains principally hydrogen and methane and possesses a calorific value almost equal to that of coal or town gas. Coke oven gas requires a minimum of 5 cu. ft. of air per cu. ft. of gas for complete combustion.

Blast furnace gas can also be used if care is taken to clean it free from dust. It is generated during the process of reducing iron ores and has a low calorific value (about 100 B.Th.U. per cu. ft.). A minimum quantity of about 0·75 cu. ft. of air is required per cu. ft. of gas for complete combustion.

Sludge gas, which is available at sewage disposal works, has a calorific value of 625 B.Th.U. per cu. ft., and contains about 66 per cent. methane. The latter is a slow-burning gas, and care in ensuring a thorough mixing of gas and air leads to increased efficiency.

Testing for correct engine operation. The indicator for a gas engine must be capable of giving an accurate diagram in spite of high engine speed and high temperature of the gases. An external stiff spring and light moving parts are essential. Fig. 112 shows an

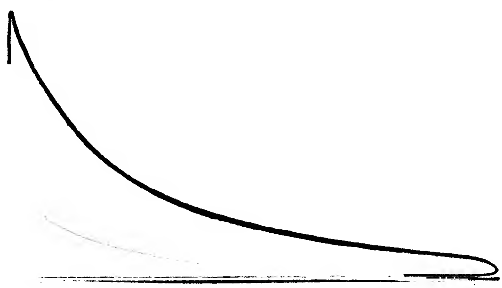


FIG. 112. Indicator diagram, gas engine.

ideal indicator card for a gas engine with correct setting of valves and ignition. Notice that the maximum pressure reached coincides with the inner dead centre when the speed was 315 r.p.m. The burning of the fuel occurs at *constant volume*, that is, by instantaneous explosion when the piston is at the inner dead centre, and then expansion follows with fall in pressure. The lowest line on the diagram indicates the suction line when the pressure is

below atmospheric. During compression the pressure line crosses the straight atmospheric line, and the pressure increases until the point of ignition causes the pressure line to become almost vertical. Expansion follows as far as the toe of the diagram, when the exhaust valve opens and the pressure line connects up with the point at the commencement of the suction stroke. The small looped diagram below the main diagram, that is, the part enclosed between the suction and exhaust pressure lines, is generally referred to as the **pumping diagram**, and registers the work which the engine has to do in drawing gases into the cylinder and ejecting them. When pre-ignition occurs, the vertical explosion line appears some little distance from the inner dead centre, so that a small loop is formed at the top of the indicator card. Late ignition can be detected on the indicator card by a hump in the expansion line between the end of compression and the opening of the exhaust valve.

Valve and ignition setting. The positions of the crank at the opening and closing of the valves for a four-stroke gas engine, with combined gas and air inlet valve to the cylinder, and also the timing of the ignition are shown by the radial lines in Fig. 113. These positions are only approximate, and depend upon the engine construction, size and speed and the type of fuel used. The exhaust and inlet valves are actually open longer than the time for one stroke, in the effort to overcome gas friction and inertia, and to evacuate and charge the cylinder rapidly. Since the valves are operated by cams, levers and rocking arms (see Figs. 110, 111 and 116), the valves are only fully open during a portion of the cam operation.

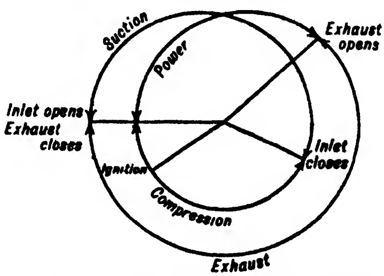


FIG. 113. Valve setting, four-stroke cycle.

In Fig. 114 a modern gas engine made by the National Gas Engine Co., Ltd., is illustrated. These engines can also be adapted to run on petrol or alcohol. Separate gas, air and exhaust valves are fitted, and these are made accessible for easy removal and for cleaning and grinding. Low-tension electric ignition is fitted in

such a way that the timing of the ignition can be varied. The magneto and ignition gear are seen at the side of the cylinder and breech end, to the right of the governor balls, and below, the half-time shaft with its cams and gear cases is clearly shown. A magneto contains permanent magnets and generates a spark in the cylinder by employing mechanical energy. The engines are fitted with a self-starter, consisting of a small hand pump, by which an initial charge of gas and air can be pumped into the cylinder and

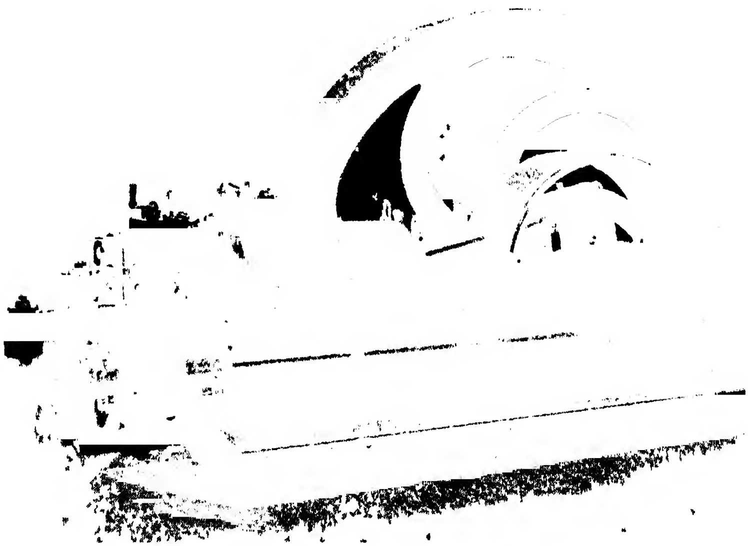


Fig. 114. A National gas engine.

ignited by means of a special lever attached to the magneto. The first impulse obtained starts the engine, and this initial motion is sufficient to carry the piston on until it draws in the working charge in the usual way. A lubricating pump is fitted, driven by an eccentric and sheave from the half-time shaft, and this pump supplies the principal bearings through glass sight feeds fitted in the supply pipes, and shown one on each side of the fuel pump. It will be seen that the lubricating pump starts and stops with the engine.

Testing of internal combustion engines. In a simple test the observations made are similar to those usually taken with the steam engine. They are:

(*a*) the diameter of the engine cylinder and piston stroke,
(*b*) the number of explosions made per minute,
(*c*) the weight or volume of the working substance used per minute,
(*d*) the condition of the fuel and its calorific value per unit weight, or volume, as supplied to the engine,
(*e*) the brake torque and the speed of the crank shaft,
(*f*) the quantity of cooling water received by the engine per minute and its temperature rise,
(*g*) the mean effective pressure in the cylinder by means of indicator diagrams.

From the above data the following calculations can be made:

Heat received by the engine per minute = quantity of fuel per min. × calorific value per unit quantity.

Indicated horse power

$$=\frac{\text{Work done per firing stroke} \times \text{no. of firing strokes per min.}}{33{,}000}$$

or

$$=\frac{nPALE}{33{,}000},$$

where P = mean effective pressure in all cylinders in lb. per sq. in.,

A = area of pistons in sq. in.,

L = stroke in ft.,

E = number of explosions per minute. This depends on the type of engine and the type of governing. For an engine taking in a charge every cycle, E = half the number of revolutions for a four-stroke cycle *or* the number of revolutions for a single-acting two-stroke engine *or* the number of engine strokes for a double-acting two-stroke engine.

n = number of cylinders.

Brake horse power, mechanical efficiency, indicated and brake thermal efficiencies, as explained on pp. 202, 205.

Heat absorbed by jacket water in B.Th.U. per min.

$=$ wt. of water per min. $\times$ temperature rise in Fahr. degrees.

$$\text{Fuel per B.H.P. hour} = \frac{\text{wt. of fuel per hour}}{\text{B.H.P.}}.$$

The latter calculation gives the rate of fuel consumption on a comparative basis.

A heat balance sheet is often drawn up, showing how the heat received by the engine per minute is disposed of. This is exemplified in examples Nos. 2, 4, pp. 268, 270. The heat which is lost to radiation and in the exhaust gases is generally assumed to effect a balance between the columns of input and disposal, when more reliable data is unavailable.

Fig. 115 shows the essential features of a high-speed Diesel engine indicator, which is capable of recording high cylinder pressures at high speeds with the minimum of error for this type of recording instrument. (See p. 192).

Example. *From the following mean data obtained during a test on a small gas engine, calculate the indicated and brake horse powers, the mechanical and thermal efficiencies, and the percentage of heat carried away in the cooling water :*

Bore, $6\frac{1}{2}$ *in. ; stroke,* 12 *in. ; r.p.m.,* 290 *; explosions per minute,* 139 *; mean effective pressure,* 64·1 *lb. per sq. in. ; gas consumption,* 2·7 *cu. ft. per min. ; calorific value of gas,* 280 *C.H.U. per cubic ft. as used by engine ; mean brake load at radius of* 20 *in.,* 74 *lb. ;* 10·1 *lb. of cooling water raised through* 29·7° *C. each minute.*

I.H.P. Work done per minute $= \pi \times \frac{169}{16} \times 64{\cdot}1 \times 139 = 295{,}250$ ft. lb.

Indicated horse power $= \frac{295{,}250}{33{,}000} = 8{\cdot}95.$

B.H.P. Work done per minute $= 74 \times \pi \times \frac{10}{3} \times 290 = 224{,}800$ ft. lb.

Brake horse power $= \frac{224{,}800}{33{,}000} = 6{\cdot}81.$

Mechanical efficiency $= \frac{6{\cdot}81}{8{\cdot}95} \times 100 = 76{\cdot}1\%.$

Indicated thermal efficiency $= \frac{8{\cdot}95 \times 33{,}000}{1400 \times 2{\cdot}7 \times 280} = 27{\cdot}89\%.$

$$\text{Brake thermal efficiency} = \frac{\text{work absorbed by brake}}{\text{energy supplied}}$$

$$= \frac{6{\cdot}81 \times 33{,}000}{1400 \times 2{\cdot}7 \times 280} = 21{\cdot}23\%.$$

$$\frac{\text{Heat to jacket water}}{\text{Heat supplied to engine}} = \frac{10{\cdot}1 \times 29{\cdot}7}{2{\cdot}7 \times 280} = 0{\cdot}397 \text{ or } 39{\cdot}7\%.$$

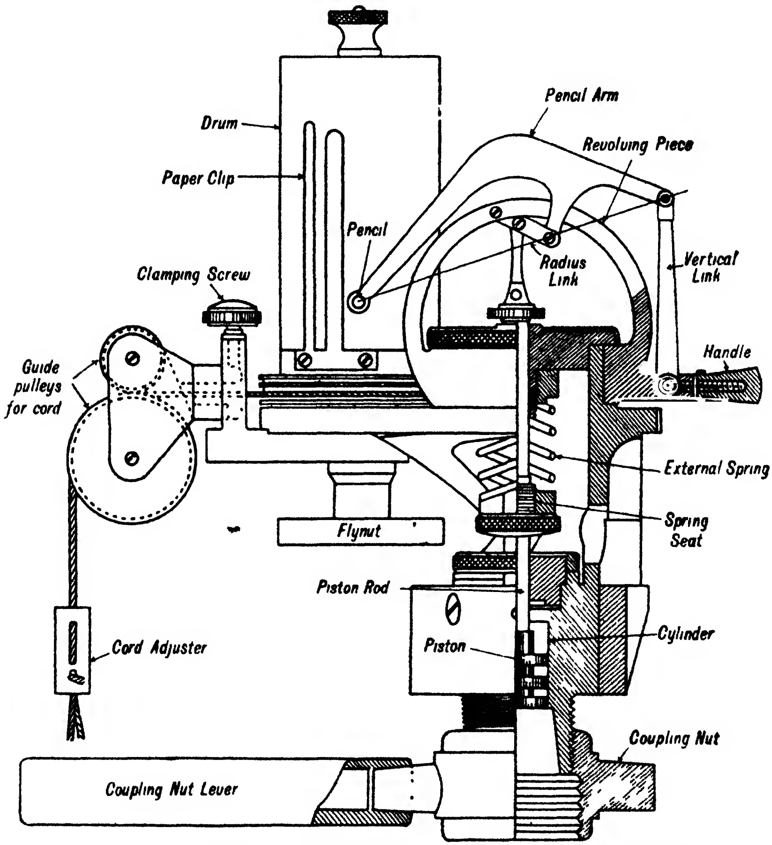


FIG. 115. Diesel engine indicator. (*Messrs. McInnes, Dobbie.*)

More worked examples are given at the end of the chapter, after other types of internal combustion engines have been dealt with.

The *efficiency of an internal combustion engine increases as the compression ratio increases*, and this can be readily understood by considering the indicator diagram. As the compression ratio increases, the clearance volume or combustion chamber volume decreases, and this means an increase in the length of the indicator diagram at the end where the pressures, and therefore the height of the diagram, are greatest.

The advantages of high compression are summarised below.

(1) More work is done per stroke, due to a higher mean effective pressure.

(2) A smaller engine is possible for the same output of energy.

(3) Economy in fuel is obtained, as weaker mixtures can be ignited more easily when highly compressed.

(4) Less spent gases remain in the cylinder at the completion of the exhaust stroke to reduce the effectiveness of the next charge.

The great disadvantage is that the high compression increases the danger of pre-ignition, especially if, as previously mentioned, there is a large hydrogen content in the gas.

Heavy-oil engines. Oil engines using heavy mineral and coal tar oils are forming an increasingly important class of internal combustion engines. In this type the fuel is forced or pumped into the cylinder about the end of the compression stroke, thus making pre-ignition impossible and permitting compression pressures to be much higher and thereby increasing the thermal efficiency. There is also less risk of fire in the storage of this heavy oil than with petrol or paraffin. With oil engines employing medium or high compression pressures the heat of compression is sufficient to ignite the fuel, and thus costly ignition gear is not required. For this reason, medium compression and high compression oil engines are often referred to as **compression ignition engines.** The earlier oil engines employed low compression, and ignition was effected by a hot bulb or uncooled extension of the combustion chamber. Oil engines can thus be classified by the degree of compression used. Later it will be seen that they can also be classified by the method of fuel injection employed or by the mode of starting the engines. High compression engines are generally called Diesel engines.

Diesel engine. The high thermal efficiency of the Diesel engine is due to the high compression ratio employed (about 14 : 1). This is made possible because pre-ignition is avoided by compressing air, and forcing the oil fuel into the cylinder in the form of a spray, at a time when the piston has reached or nearly reached the end of the compression stroke. The heat of compression reached at the dead point position causes spontaneous combustion, and the burning of the fuel maintains the compression pressure during the power stroke until the fuel is cut off. Diesel engines thus work on what is called the **constant pressure cycle**, because the heat generated by the combustion of the fuel is given to the engine at approximately constant pressure. Gas engines are said to work on the **constant volume cycle**, because the heat is developed instantaneously by the explosion of a mixture of fuel and air while the piston is momentarily stationary. The Diesel engine is noted for its smooth and comparatively quiet running, due to the absence of any explosion during each cycle. Medium-compression heavy-oil engines which work partly on the constant pressure and partly on the constant volume cycle, or **dual cycle** as it is sometimes called, are often termed **semi-Diesel** engines. The low-compression hot-bulb type of oil engine working on the constant volume cycle is also often called a semi-Diesel engine, so that the term has little to commend it except usage. The maximum compression pressure is lower in the latter engines, which admits of lighter and less costly engine construction.

Strictly speaking, the semi-Diesel engine is one in which the oil charge is sprayed directly into a combustion chamber, and it is ignited by the heat of an uncooled part of this chamber together with the heat generated by the moderate compression of the air. The charge is injected at about the time of maximum air compression in the cylinder, and the combustion takes place at approximately constant volume.

Fig. 116 shows a longitudinal section of a Crossley Premier horizontal Diesel engine, which works on the four-stroke Otto cycle. It shows clearly the mode of valve operation by cams and levers usually associated with internal combustion engines. Lubrication is carried out by a pump to the main moving parts, the streams of oil passing through visible glass plates, and these streams can be con-

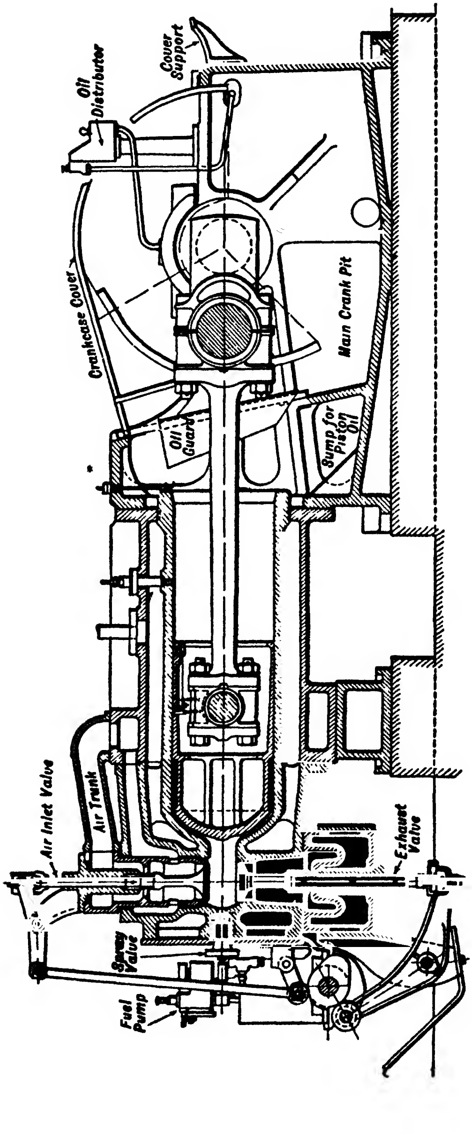


FIG. 116. Longitudinal section. Crossley Premier Diesel engine. (*By courtesy of Messrs. Crossley.*)

trolled by needle valves. The used oil drains back into the sump through filters and can be used over again. These engines can be converted in about two hours to run on gaseous fuels, and they are very economical and efficient, a six-cylinder engine developing 750 B.H.P. It will be noticed that the engine is well cooled, provision being made for cooling around the valves.

Principles of fuel injection. In the Crossley Premier Diesel engine the fuel is pumped and sprayed into the cylinder, without the aid of compressed air, and this method is termed **airless or solid injection.** The early Diesel engines were all of the air-injection type in which high-pressure air was used to force the fuel into the cylinder. In the process of injection it is important to see that:

(*a*) the correct quantity of oil is delivered during each working stroke;

(*b*) the injection is made at the point of maximum compression and at the correct rate to maintain constant pressure in the cylinder during combustion;

(*c*) to divide the oil into as fine a spray as possible and distribute it evenly throughout the combustion chamber.

When the fuel is driven by a blast of air into the compressed and hot mass of air at the end of the compression stroke of the engine, it is referred to as **air-blast injection** or simply **air-injection.** This method has the advantage that the fuel is better distributed in the combustion chamber, which leads to economy in fuel consumption. The disadvantages are that (*a*) the cooling effect of the cold blast of air hampers combustion, and (*b*) a costly air-compressing plant capable of dealing with pressures of about 1000 lb. per sq. in. has to be used, a plant which absorbs about 6 per cent. of the whole output of the engine. Improvement has been made by employing compact three-stage air compressors with the cooling of the air between each stage. In this way mechanical difficulties have been overcome, but the increased power required must always be considered.

In the air-injection system oil is pumped in small charges, each just sufficient for one firing stroke, into the casing around the injection valve. This casing is also kept charged with high-pressure air

and, when the injection valve is lifted off its seat at the right moment by means of a cam and system of levers, the oil charge is blown with great force into the combustion chamber through holes in the nozzle uncovered by the valve.

With the airless or solid type of injection the fuel is forced by a pump directly through a nozzle with very fine holes at a pressure of from 4,000 to 10,000 lb. per sq. in. in order to ensure a fine spray spreading throughout the combustion chamber. There are many different forms of airless injection and, in every type, great care is necessary to prevent the very fine nozzle holes from becoming clogged, even temporarily.

In the case of the so-called semi-Diesel type of engine, the fuel inlet valve is not operated by a cam but is forced open, against the pressure exerted by its closing spring, by the fuel pump delivery pressure, and the whole of the oil required for one firing stroke is suddenly sprayed into the combustion chamber or a specially heated extension of it. In the latter case the extension is referred to as the **hot bulb**, the presence of which produces practically instantaneous combustion and a rise of pressure considerably above that reached at the end of compression. There are now a large number of medium-compression heavy-oil engines in which the hot bulb has been entirely dispensed with, the automatic ignition of the charge being arranged by increasing the compression pressure just sufficiently to ignite the charge. These are also generally classed by engineers as " semi-Diesels," because the combustion is partly at constant volume and partly at constant pressure ; hence the compression pressures are less than in the true Diesel engine, *i.e.* an engine in which the pressure reached is never higher than that reached at the end of compression. A **cold starting engine** is one which does not require a hot bulb or the application of heat to a portion of the combustion chamber.

Diesel fuels. The types of fuel suitable for Diesel engines are (*a*) the crude and residual heavy petroleum oils of specific gravity 0·85 to 0·95 at 60° F., and having a calorific value of from 18,500 to 19,500 B.Th.U. per lb. ; oils of an asphalt base which tend to gum-up the valves are unsuitable ; (*b*) the coal tar oils of specific gravity 1 to 1·1, and of calorific value 16,000 B.Th.U. per lb. ;

these oils require a very high temperature to start ignition, and this difficulty has been overcome by introducing a more readily combustible oil prior to introducing the coal tar oil.

Diesel engine indicator cards. Fig. 117 shows typical indicator cards, one for a four-stroke and one for a two-stroke Diesel engine,

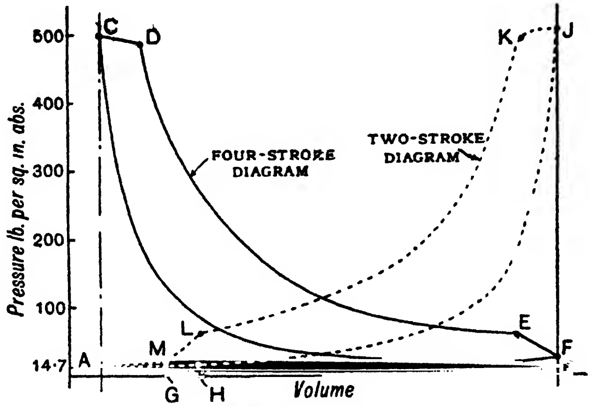


FIG. 117. Diesel engine indicator cards.

both being of the air-injection type ; the card for the latter engine is reversed so as not to cause confusion. The effect of the main operations of the engines are shown in the indicator diagrams, those for the two-stroke are added for comparative purposes, and should be studied in conjunction with the description of the Petter engine which follows.

Four-stroke.

1. Suction of air, A to B, below atmospheric pressure.
2. Compression, B to C, up to about 500 lb. per sq. in. abs.
3. Combustion, C to D, practically at constant pressure.
   Expansion, D to E, falling pressure.
4. Exhaust, E to F and F to A, at slightly above atmospheric pressure. The exhaust valve begins to open at E.

Two-stroke.

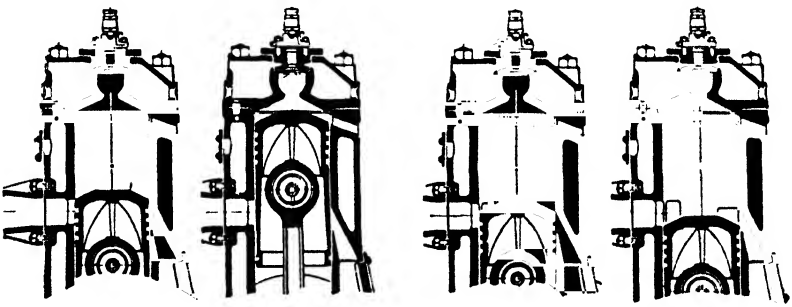
1. Suction, A to H, slightly below atmospheric pressure.
2. Compression, H to J, up to 500 lb. per sq. in. abs.

3. Combustion, J to K, practically at constant pressure.
   Expansion, K to L, falling pressure.
4. Exhaust, L to G, at about atmospheric pressure.
   Scavenging, M to A and A to G.

Broadly speaking, the four-stroke engine is preferred for high speeds when effective scavenging or removal of the exhaust gases is important, and this is difficult to achieve in the two-stroke engine. For high powers and low speeds, the two-stroke engine is finding favour, especially when it is double-acting. The two-stroke engine has the higher mean temperature during a cycle, and consequently is the more difficult to cool satisfactorily.

Vertical two-stroke Diesel engine. It is proposed to deal now with a Diesel engine, which will illustrate the two-stroke constant pressure cycle of operation and the principle of the Diesel engine at the same time. The engine is made by Messrs Petters, Ltd. of Yeovil, now of Loughborough, to whose courtesy the illustrations are due

The two-stroke cycle. This cycle is completed in each revolution of the crank shaft, and the exhaust valve in practice is replaced by ports, which are covered and uncovered by the piston itself. Fig. 118 shows the complete cycle of operations. In A the piston is



A B D E

FIG. 118. Two-stroke cycle.

moving upwards and has just closed the exhaust ports on the left and also the air trunk inlet on the right. Compression of the air in the cylinder follows, and just prior to the piston reaching the top of its stroke (Fig. 118, B) the injection of the oil fuel commences.

The heat of compression causes the fuel to ignite spontaneously as soon as the dead centre is reached, and it burns approximately at constant pressure until the supply is cut off, the actual point of cut-off being controlled by the governor. Expansion of the hot gases follows, which forces the piston downwards and provides the impulse or working stroke.

When the piston reaches the position shown in diagram D the exhaust ports are being uncovered, and the spent gases can expand down to atmospheric pressure. As the downstroke nears completion (diagram E), the air ports on the right are uncovered, allowing a current of scavenge air at a gauge pressure of about 3 lb. per sq. in. to be directed upwards through the coned ports, past the conical crown of the piston, to the top of the combustion chamber. The latter is conical and smooth and deflects the air downwards, sweeping the exhaust gases before it. Fig. 120 shows clearly the direction of flow of scavenge air, and scavenging continues until the piston returns to cover the air ports as shown in diagram A (Fig. 118).

Principles of operation. Fig. 119 illustrates piston positions in the centre diagram, and crank positions on the right-hand diagram, at

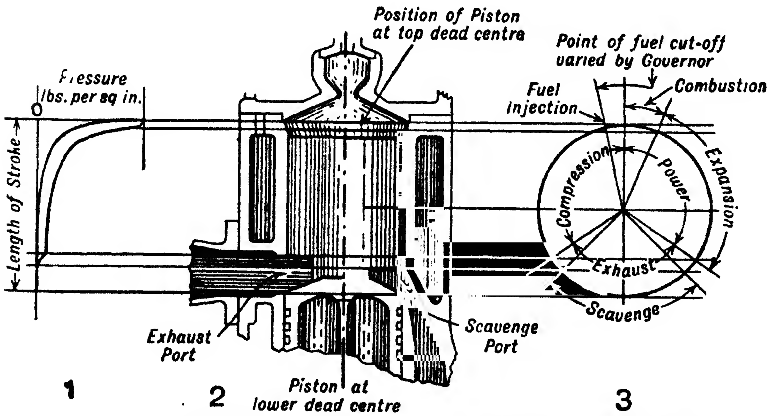


FIG. 119. Principles of operation for two-stroke Diesel engine.

the commencement and completion of the major operations of combustion, expansion, power, compression, exhaust and scavenging.

The left-hand diagram shows a typical indicator card. It is worthy of notice that the indicator diagram shows that the pressure reached

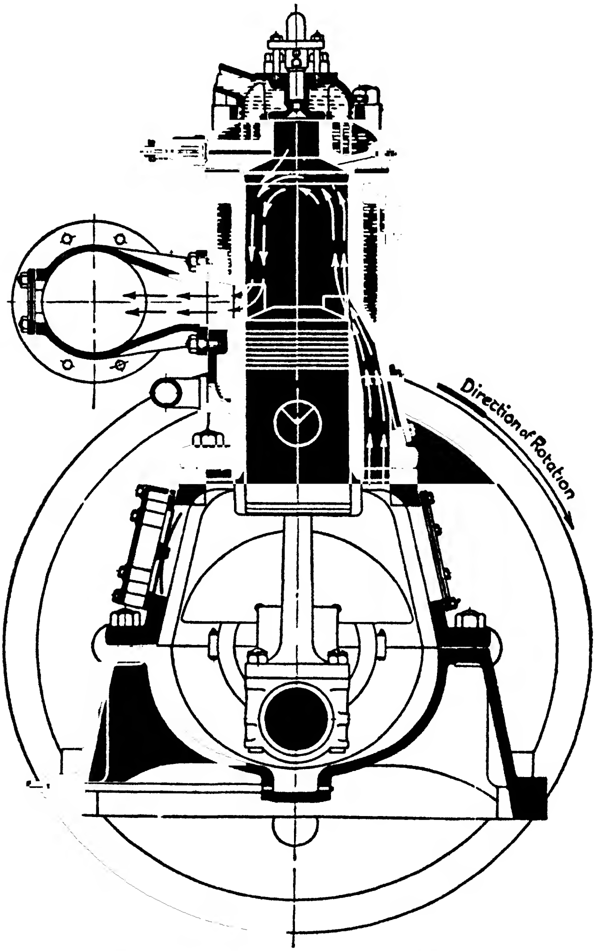


FIG. 120. Cross-section, two-stroke Diesel engine.

at the end of the compression stroke remains practically constant, for the short period while the fuel is being burnt, up to the point of

cut-off; also that as soon as the exhaust valve is opened the pressure drops to about atmospheric pressure and remains so during scavenging.

Air for scavenging is drawn into the crank case through thin flexible inlet plates fitted over narrow ports on a door in the upper half of the crank case. This air is drawn in during the upstroke of the piston until the top of the stroke is reached and is compressed on the downstroke, the rising pressure automatically closing the air plates, causing them to act as non-return valves. When the air ports to the cylinder are uncovered bv the piston, this air being under pressure rushes through the ports, drives out the exhaust gases and tends to cool the cylinder. A compressor for scavenge air is necessary on the two-stroke cycle.

Fuel oil is injected into the cylinder through an atomiser, centrally placed in the cylinder cover, in the form of a cone-shaped spray. The minute particles of oil mix intimately with the highly compressed and turbulent air, producing efficient and almost complete combustion. No alteration is made in the pressure forcing the fuel through the atomiser for variations of engine speed and load.

Details of construction. Fig. 120 shows a section through the engine, with its water-cooling and scavenging arrangements, and the position of the atomiser. The bedplate forms the lower portion of the crank case, and is extended on the governor side in the single cylinder engine to take the operating and control gear, and to provide an oil sump for the fuel pump and governor operating gear. The upper portion of the crank case is a separate casting bolted to the bedplate, and the cylinder is bolted to and supported by the crank case. It will be noticed that the cylinder head is provided with a water jacket, the upper portion being detachable from the lower so as to give access to the water space for cleaning. Fig. 121 shows the cylinder head with the atomiser in position. Cooling water enters at the bottom of the cylinder jackets, passes through ports into the cylinder head, and leaves through the pipe at the top. The cylinder head is also provided with a compression relief plug, shown to the left of the atomiser, while its inside surface is machined all over to lessen gas friction. The crank shaft

for a single cylinder engine is shown in Fig 122; it is machined from a solid forging and provided with balance weights Fitted to one of the crank webs is a grooved oiling ring, which receives oil

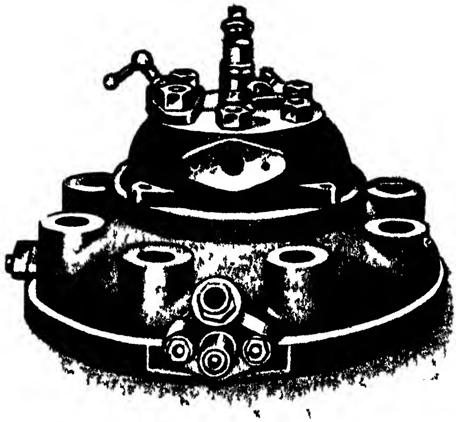


FIG 121 Cylinder head

from a fuel pump and delivers it to the crank pin by centrifugal force as it revolves with the web

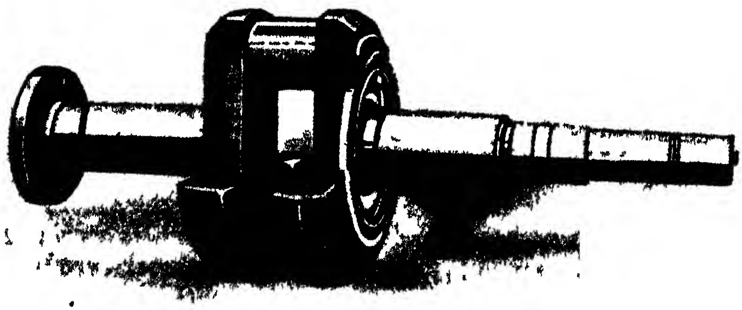


FIG. 122 Crank shaft

In Fig. 123 a main bearing is illustrated, the cast iron cap being lifted to show the solid oiling ring. The two halves of the bearing

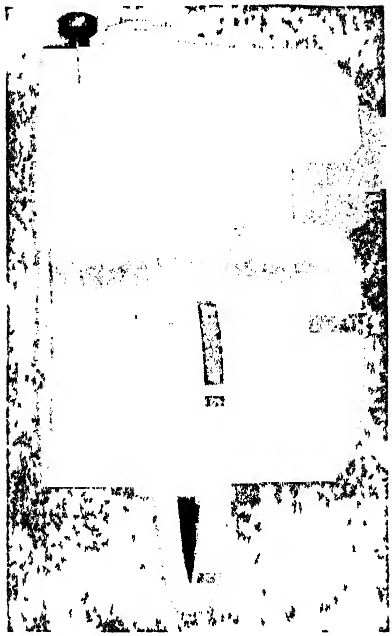


FIG. 123. Main bearing.

are made of gun metal lined with white metal to lessen friction. Oil is lifted by the large oiling ring, from an oil well, to the top of the shaft, while this ring is dragged slowly round by the shaft. The assembly of the piston and connecting rod and gudgeon pin are shown in Fig. 124. The illustration also shows how the piston rings are kept from rotating by small stops or pegs, the pegs being staggered so that they are not in one straight line. A set screw is

FIG. 124. Piston and connecting rod assembly.

used to fasten the gudgeon pin to its bearings or bosses in the piston, the pin being previously carefully ground to size. It is the practice to relieve the stresses set up in the piston, due to unequal contraction during cooling of the casting, by subjecting it to special heat treatment.

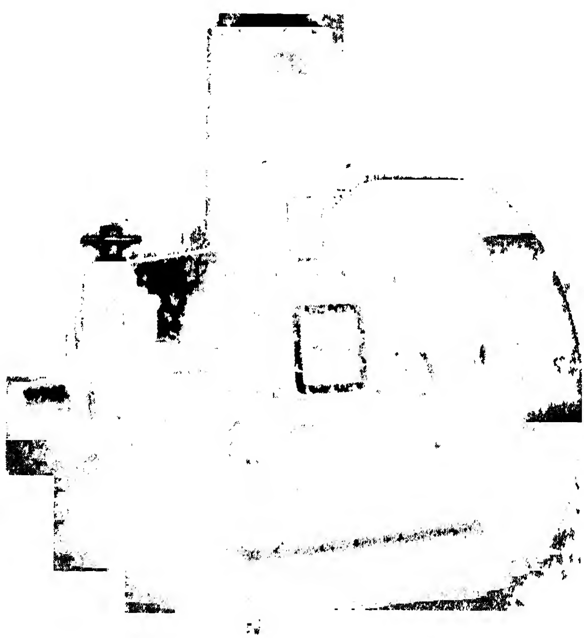


FIG 125. Single cylinder, two-stroke, Diesel engine.

To lubricate the small end of the connecting rod as it oscillates about the gudgeon pin brass wipers are fitted to the ends of the latter, and these by pressing lightly against the cylinder walls collect oil and deliver it to the bearings. The connecting rod is made of high tensile valve steel and is of I section, to make it light and well able to resist bending. A complete single cylinder engine is illustrated in Fig. 125, its output being 90 B.H.P. The flywheel

is of the solid disc type, machined on faces and rim, carefully balanced and bolted firmly to a flange, forged solid with the crank shaft, to secure perfect alignment.

Fuel supply and governing. The fuel pump plunger is operated by a cam driven from the crank shaft, and this cam is fitted with adjusting screws and lock nuts so that the timing of the fuel injection can be adjusted. The plunger commences to deliver a full charge of oil through the non-return delivery valve to the atomiser, but at a certain period of its stroke a small spill valve plunger, controlled by the governor, lifts a by-pass or spill valve from its seat and allows the remainder of the charge to be by-passed back to the fuel supply. This small spill valve plunger is actuated by the governor itself, which thus determines the amount of charge reaching the atomiser.

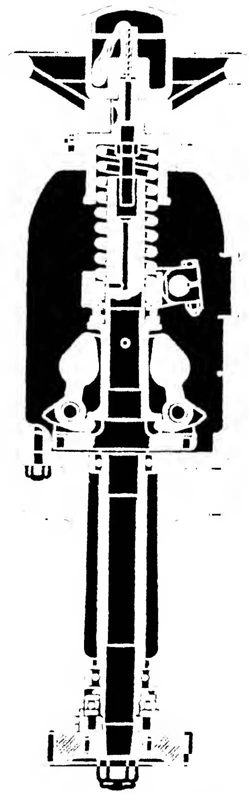


Fig. 126. Section through governor.

Fig. 126 is a section through the governor, which is of the centrifugal type mounted vertically and driven from the crank shaft by helical gearing. Ball bearings are provided to lessen friction, and all the revolving parts are enclosed in an oil-tight casing. As the speed increases the governor weights move outwards and the bell crank levers lift the sleeve against the spring load. To this sleeve is connected the governor control shaft which controls the opening of the spill or by-pass valve. At the top of the governor, a hand wheel is provided for reducing the engine speed while it is running. In operation the hand wheel adjusts the load on the governor spring, and thus raises or lowers the speed range controlled by the governor.

Fig. 127 shows a section through the atomiser. Fuel enters by the pipe on the right to an annular chamber surrounding the needle holder (marked 3), and when the necessary pressure is exercised by the fuel pump plunger the needle valve (marked 2) is lifted against a spring and the oil is sprayed through fine holes drilled radially in the nozzle. The fuel injection is maintained until the spill valve by-passes the remainder of the charge. A ball valve (marked 13) held to its seating by a small thumb screw is used as an air release valve to allow of the fuel injection system being primed or precharged before starting.

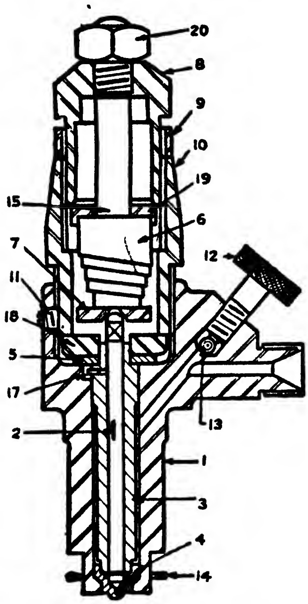


FIG. 127. Atomiser, closed nozzle, airless injection type.

2. Needle.
3. Needle holder.
4. Nipple.
6. Spring.
7. Spring carrier.
12. Release screw.
13. Ball valve.
15. Needle stop.

For the engine illustrated in Fig. 125 starting is effected by compressed air, at 350 lb. per sq. in., which is stored in receivers filled by a compressor, driven by a belt from a driving pulley on the main engine shaft on to fast and loose pulleys on the compressor shaft. The belt is transferred to the loose pulley when the compressor is not working. It is necessary to water-cool the air compressor to abstract the heat gained by the air during compression and so prevent overheating. The compressor used is of the reciprocating type.

Advantages of this two-stroke Diesel engine.

(1) Simplicity of design. (2) No valve grinding required, as there are no valves. (3) No air compressor for fuel injection, as the latter is airless. (4) Compact design and small area of foundation. (5) Economical in fuel and lubricating oil consumption. (6) Easy starting and control.

The harmonic induction engine. Messrs. Petters, Ltd., of Yeovil, have introduced a two-stroke Diesel engine, in which the exhaust gases are expelled from the cylinder and a new charge of clean air introduced, solely by taking advantage of the harmonic pulsations in this exhaust system. This engine requires no separate compressor and does not employ crankcase compression, starting being effected by hand under cold conditions. Since, in this design, induction and exhaust depend upon the wave-length in the exhaust system, considerable attention has to be given to the situation and arrangement of this exhaust system, but the use of an engine of this type presents very marked advantages in operation *for constant speed work.* This engine provides a high cyclic regularity in power, a power stroke in each revolution, a low power weight ratio, and clean exhaust at all loads.

The makers estimate that an engine of 16 B.H.P. to this design will have a fuel consumption below 0·4 pints per B.H.P. per hour on full load, and that this figure remains practically constant over a wide range from half load to 10 per cent. overload. The lubricating oil consumption is less than 0·004 pints per B.H.P. per hour, the engine is efficiently silenced, and the ordinary thermo-siphon system of cooling is effective.

The petrol engine. Space will not allow of a detailed study of this engine, but a few of its main features can be dealt with. The great majority of petrol engines work on the four-stroke Otto cycle, uniformity of effort and speed being obtained by increasing the number of cylinders and components actuating one shaft, and varying the firing so that the power or effort is spread over the revolution. By employing a number of cylinders (now standard practice with all internal combustion engines except very low powers) a smaller flywheel can be used, and this again is made possible by the high speed of revolution of petrol engines. In these circumstances a lighter flywheel can prevent, successfully, violent fluctuations of speed during the cycle of operations. The high speeds also entail that the moving parts of the engine be strong but light, so that the forces necessary to accelerate and retard the reciprocating parts during each stroke may be reduced to a minimum. These forces are proportional to the mass of the reciprocating parts, and unless they

are minimised or balanced, lead to balancing troubles, vibration and unnecessary straining of the engine. The petrol engine differs from other internal combustion engines principally in the manner of obtaining an explosive mixture of fuel oil and air. For this purpose a carburetter is used.

The carburetter. The function of a carburetter may be divided into three parts: (*a*) to discharge into the air stream entering the engine the required amount of fuel, (*b*) to break up or atomise that fuel, (*c*) to make as uniform a mixture as possible. Carburetters vary a great deal in detail, but all conform to the above-mentioned principles. The most simple form of carburetter is shown in Fig. 128, in which the level of petrol is controlled by a float operating a needle valve. Petrol flows or is pumped into this float chamber until the rising float closes the valve. The level of petrol then allows of some escaping through a fine jet, which is placed at the narrowest portion or throat or choke tube in the main air supply to the engine. The suction produced by the latter draws air through this throat in the induction pipe, and the reduced diameter causes an increase of velocity and a reduction of pressure there, in the same way as in the Venturi meter. The high velocity and low pressure in the throat facilitate the breaking up of the petrol and its admixture with the air. In order to control the supply of mixture to the cylinders, and consequently the engine speed, a butterfly valve or throttle valve is placed in the induction pipe, and this is shown above the throat in the diagram. A wide open throttle will allow of the maximum suction and supply of explosive mixture to the engine.

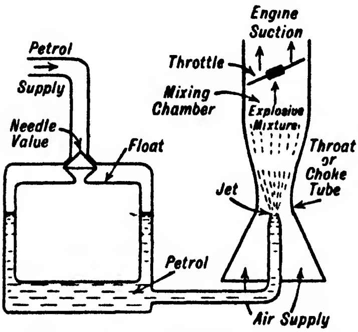


FIG. 128. Principle of carburetter.

Fig. 129 shows a modern Zenith type 30VM down-draught carburetter in section. Besides the main parts already mentioned in the simple carburetter, it has many refinements and compensations to adapt it and make it efficient over a variety of engine speeds and

loads. Before entering the float chamber (4) the petrol passes through a filter. When the petrol has filled the passages (13) and (14), the capacity tube (9), and passages (15) and (17), as well as the float chamber, the petrol float (5) cuts off the supply by forcing the needle valve on to its seating, and the carburetter is said to be

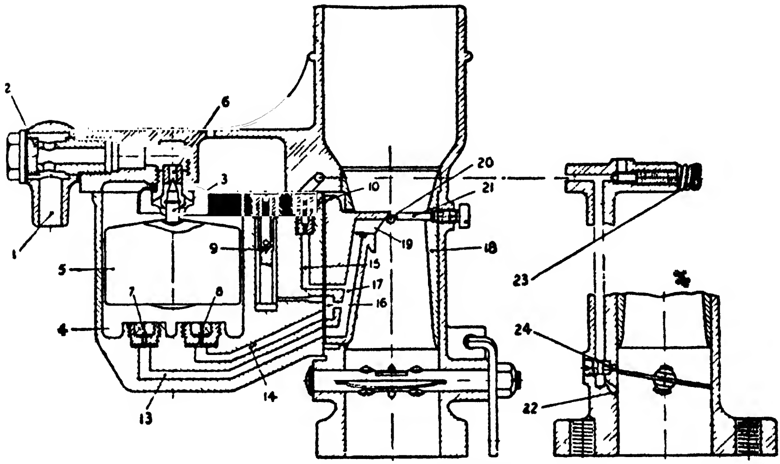


FIG. 129. Zenith carburetter.

Sectional View of Type 30 VM.

1. Petrol union.
2. Filter.
3. Needle.
4. Float chamber.
5. Float.
6. Needle seating.
7. Main jet.
8. Compensating jet.
9. Capacity tube.
10. Slow running jet.
16. Emulsion block.
18. Choke tube.
20. Distributor bar.
21. Choke screw and third bar.
23. Slow running air adjustment screw.
24. Progression jet.

flooded. It must be remembered that the compensating jet, capacity tube and slow running jet, etc., are refinements for certain conditions of running, and that the main jet and passages (13) and (17) are primarily the essential parts. When the engine is running normally, air flows in through the pipe shown at the top of the diagram down past the distributor bar (20), choke screw and bar (21), creating a partial vacuum in the throat, especially beneath these bars, causing the petrol to flow from passage (19) across the throat and mix with

the incoming air. The mixture then flows down through the butterfly valve to the induction pipe.

It will be noticed that the capacity tube is in communication with the atmosphere, and as this tube is soon emptied of petrol when the engine first starts up with opening throttle valve, air becomes mixed with the petrol (at 16) coming from the compensating jet. The air breaks up the petrol and the emulsified mixture formed meets the petrol flowing from the main jet along (17), tending to break up this petrol also. The supply from both sources will then be drawn from the emulsion block nozzle (19) into the throat or choke tube. In this way a very rich mixture is available for rapid or progressive getaway from slow running.

For slow running, to keep the engine " ticking " over when the butterfly valve is nearly closed, petrol is drawn from the slow-running jet past an adjustable air supply, and the mixture enters the induction pipe through the small hole shown just below the butterfly valve. These carburetters are also fitted with a special automatic starting device.

The car engine. A section through one cylinder of a four-cylinder Standard 10 H.P. car engine is shown in Fig. 130. The bore or diameter of the cylinders is 63·5 millimetres, while the stroke of the pistons is 106 millimetres. A brake horse power of 32 is developed at a peak speed of the crank shaft of 3600 r.p.m. No governor is fitted as the inertia of the car gives ample time for hand adjustment of fuel supply to meet the needs of the moment.

The cylinders are off-set from the crank shaft axis (Desaxé principle) with the idea of reducing the side pressure of the piston on the cylinder, due to the connecting rod being inclined, during the down explosion stroke. Chromium iron is used in the construction of the cylinder blocks, but the pistons are made of aluminium and the connecting rods of a light steel alloy. The valves (inlet and exhaust) are placed side by side and lifted by cams giving simple harmonic motion to the valve spindles. Only one valve is shown, but the valve cam and the method of actuating the valve rods and tappets and the controlling springs are clearly seen. The oil sump is filled to the desired level through the oil filler shown, a dip stick being

used to determine this level. From the sump the oil is pumped to the engine bearings by a submerged gear type of pump in the oil sump which forms the lower half of the crank case.

The current for the electric starter for the engine, the ignition and lighting is derived from accumulators which are kept charged by a

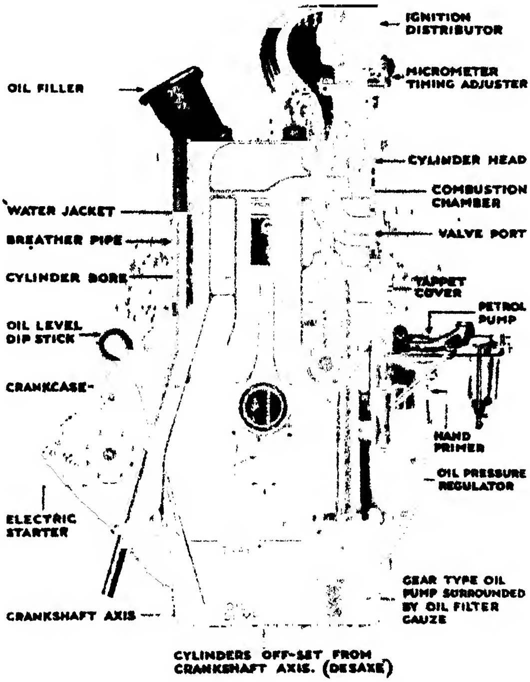


FIG. 130. Section through one cylinder of a motor-car engine.

small dynamo driven from the engine. The ignition distributor with adjuster is shown, whereby the current of electricity can be directed in turn to each cylinder so as to produce a spark at the correct moment.

Coil and battery ignition. A common method of producing a spark for a petrol motor is by what is known as coil and battery

ignition. The principle employed is that of the induction coil, and a diagrammatic sketch is shown in Fig. 131a. The essential parts are a soft iron core surrounded by a primary coil consisting of a few turns of stout wire, and this primary coil is surrounded by a secondary coil consisting of a large number of turns of fine wire. By suddenly stopping the current in the primary circuit by means of the contact breaker, a current of much higher voltage is induced in the secondary coil. When the double pole switch (Fig. 131a) is closed, part of the current flows from the positive pole of the battery

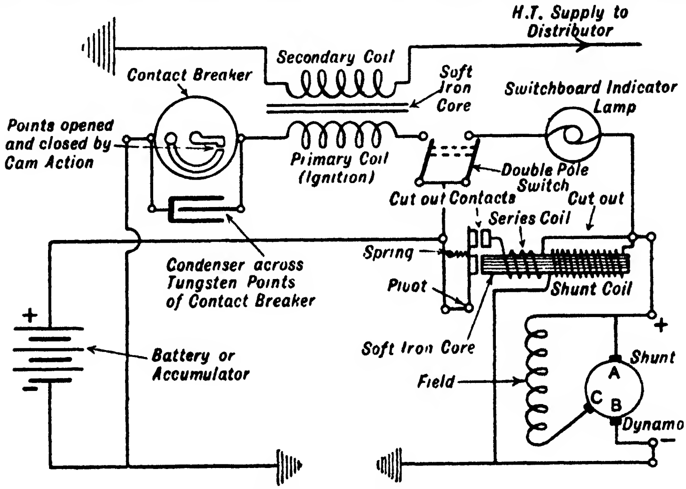


FIG. 131a. Principle of coil and battery ignition for a car.

through the primary coil and contact breaker and part through the filament of an indicator lamp on the dashboard. In a four-cylinder engine a cam ring actuated by the engine itself causes the tungsten points of the contact breaker to be sharply separated twice in each revolution so that two correctly timed surges of high voltage or high tension (H.T.) current pass from the secondary coil to the distributor. Fig. 131b shows how one end of the secondary coil, connected to the revolving contact arm of the distributor, feeds the high voltage current to each sparking plug in such a way that the firing order is 1, 3, 4, 2 in the respective cylinders. This current is conveyed in turn to the centre pin of a sparking plug, which is screwed

into the engine cylinder, but this centre pin is insulated from the body of the plug. The other end of the secondary coil is connected to the engine frame, so the circuit can only be completed by the current crossing the air gap in the cylinder between the sparking points and the centre pin of the plug in the form of a spark or series of sparks. As the secondary current is of high voltage, it assists the passage of the current across the air gap, which is about $\frac{1}{50}$ of an inch. Modern practice inclines towards making the centre pin negative as this involves less wear on this part. The electrical condenser inserted across the contact points prevents excessive sparking.

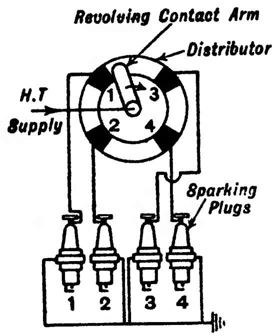


FIG. 131b.

When the car engine has gathered speed the terminal voltage of the shunt dynamo (Fig. 131a and p. 341), which is driven by the engine, rises above that of the battery. The dynamo then "cuts in" to supply low tension current for the primary ignition circuit and also current to charge the battery. Similarly, the dynamo is cut out when its speed drops and the voltage it generates falls below that of the battery.

Commercial applications. In the use of I.C. engines it is often necessary to extend the ordinary engine tests to obtain specific results which bear on the engine performance. In the following examples representative illustrations are taken of some of the actual requirements in (*a*) gas producer plant, (*b*) Diesel operation, (*c*) Diesel engine coupled to a generator, (*d*) automobile working. In each of these cases, certain results are of value, and these can be obtained by direct inference from the ordinary tests. For example, in automobile work, given the gear ratios and road wheel diameter, road speed can be obtained, and thence the fuel consumption in miles per gallon. Further, in the Diesel-generator type, details of generator output can be observed and overall efficiencies obtained, with particulars of the performance when used as a locomotive. The making out of a heat balance sheet always proves instructive, as faults are made readily apparent and may be remedied.

Worked examples.

Example 1. *Determine the thermal efficiency of an oil engine which uses 0·39 lb. of oil per B.H.P. hour if the calorific value of the oil is 19,500 B.Th.U. per lb. If the engine develops 20 I.H.P. and the mechanical efficiency is 80%, calculate the brake horse power and the fuel consumption per hour.*

Heat to engine $= 0{\cdot}39 \times 19{,}500$ B.Th.U. per B.H.P. hour.

Heat equivalent of 1 B.H.P. hour $= 33{,}000 \times 60 \div 778$ B.Th.U.

$$\therefore \text{ Brake thermal efficiency} = \frac{33{,}000 \times 60}{778 \times 0{\cdot}39 \times 19{,}500} \times 100 = \mathbf{33{\cdot}47\%}.$$

$$\text{B.H.P.} = \frac{80}{100} \times 20 = \mathbf{16}.$$

Fuel consumption per hour $= 16 \times 0{\cdot}39$ or **6·24 lb.**

Example 2. *The following figures are taken from a test on a combined gas engine and producer plant :*

Producer. *Coal consumption—84 lb. per hour.*
Calorific value of coal used—13,000 B.Th.U. per lb.
Gas generated—64 cu. ft. per lb. of coal.
Calorific value of gas—175 B.Th.U. per cu. ft.

Engine. *Speed—225 r.p.m.*
Horse power developed—112 B.H.P.
Explosions—83 per minute.
Mean effective pressure—93 lb. per sq. in.
Bore—18 in. and stroke 27·7 in.
Jacket water—70 lb. per min. with a rise of temperature of 72° F.

Calculate the overall efficiency of the plant and draw up a heat balance.

Heat available in coal with complete combustion

$= 84 \times 13{,}000 \div 60$ B.Th.U./min.

$= 18{,}200$ B.Th.U./min.

Heat supplied to engine per min. in producer gas

$= 64 \times 175 \times 84 \div 60$ B.Th.U./min.

$= 15{,}680$ B.Th.U./min.

Heat lost in gas producer $= 18{,}200 - 15{,}680$ or **2,520 B.Th.U./min.**

Heat to the jackets $= 70 \times 72$ or **5,040 B.Th.U./min.**

Heat to brake $= 112 \times 33{,}000 \div 778$ or **4,750 B.Th.U./min.**

$$\text{I.H.P.} = \frac{\text{work per firing stroke} \times \text{no. of explosions per min.}}{33{,}000}$$

$$= \frac{93 \times \pi \times 18^2 \times 27{\cdot}7 \times 83}{4 \times 33{,}000 \times 12} = 137{\cdot}4.$$

Heat equivalent of I.H.P. $= 137{\cdot}4 \times 33{,}000 \div 778$ or 5,828 B.Th.U./min.

Heat supply lost in engine friction $= 5{,}828 - 4{,}750$ B.Th.U./min.

$= 1{,}078$ B.Th.U./min.

Overall thermal efficiency $= \frac{4{,}750}{18{,}200} \times 100 = 26{\cdot}1\%$

Heat balance	B.Th.U. per min.		B.Th.U. per min.	%
Heat supplied to plant per min.	18,200	Heat lost in producer -	2,520	13 9
		,, to brake - -	4,750	26·1
		,, lost in engine friction - -	1,078	5·9
		,, lost in jacket water	5,040	27·7
		,, lost to exhaust and to radiation (by difference) -	4,812	26·4
	18,200		18,200	100%

xample 3. *The minimum air required per lb. of fuel for a Diesel engine is* 14 *lb., while an analysis showed that the air actually passing into the cylinders was* 2 5 *times the minimum. Calculate the heat carried off by the products of combustion and by the excess air per lb. of fuel when their temperature was* 900° *F. The temperature of the air at inlet was* 50 *F. Specific heat of products of combustion* = 0 25 *and specific heat of air* 0·24.

Products of combustion per lb. of fuel $= (14 + 1)$ or 15 lb.

Excess air $= (2\frac{1}{2} \times 14 - 14)$ or 21 lb.

Heat carried away by the products of combustion per lb. of fuel

$= 15 \times (900 - 50) \times 0{\cdot}25$

$= 3187$ **B.Th.U.**

Heat carried away by excess air $= 21 \times (900 - 50) \times 0{\cdot}24$

$= 4284$ **B.Th.U.**

Example 4. *If in Example 3 the engine generated 25 I.H.P. with a fuel consumption of 9·3 lb. of oil per hour, draw up a simple heat balance sheet to show how the heat supplied is utilised or wasted by the engine. Take the calorific value of the oil as 19,500 B.Th.U. per lb.*

$$\text{Heat to indicated work per lb. of fuel} = \frac{25 \times 33{,}000 \times 60}{9 \cdot 3 \times 778} \text{ B.Th.U.}$$

$$= 6{,}841 \text{ B.Th.U.}$$

Calorific value of fuel $= 19{,}500$ B.Th.U. per lb.

Heat balance	B.Th.U. per lb. of fuel		B.Th.U. per lb. of fuel	%
Heat supplied (per lb. of fuel)	19,500	Heat to I.H.P. - -	6,841	35
		,, to products of combustion - -	3,187	16·4
		,, carried away by excess air -	4,284	22
		,, to jackets or radiation by difference	5,188	26 6
	19,500		19,500	100%

Example 5. *A Diesel-electric rail car, in which the engine is coupled directly to a generator, weighs 36 tons, and the total resistance to motion is 20 lb. per ton when the speed is 45 m.p.h. on the level. The generator supplies current to the motors, the output being 400 amperes at 180 volts. The fuel consumption is 44 lb. per hour. If the calorific value of the oil used is 19,500 B.Th.U. per lb., calculate :*

(*a*) *The thermal efficiency of the combined engine and generator.*
(*b*) *The efficiency of the combined motors and gears.*
(*c*) *The fuel cost per H.P. hour used up at the rail.*

Take the specific gravity of the oil fuel as 0·83 and the cost as 6d. per gallon.

$$45 \text{ m.p.h.} = 66 \text{ ft. per sec.}$$

$$\text{Work done at the rail per second} = \overbrace{36 \times 20 \times 66}^{\text{Resistance} \times \text{Speed}} \text{ or } 47{,}520 \text{ ft. lb. per sec.}$$

Output of generator

$$= 400 \times 180 \text{ or } 72{,}000 \text{ watts or } \frac{72{,}000 \times 33{,}000}{746} \text{ ft. lb./min.}$$

$$= 3{,}185{,}000 \text{ ft. lb./min.}$$

$$\text{Input of energy from fuel} = \frac{44 \times 19{,}500 \times 778}{60} \text{ ft. lb./min.}$$

$$= 11{,}125{,}400 \text{ ft. lb./min.}$$

Fuel cost per hour $= \dfrac{44 \times 6}{10 \times 0{\cdot}83}$ pence, since 1 gallon of oil weighs $10 \times 0{\cdot}83$ lb. and 1 gallon of water weighs 10 lb.,

$$= 31{\cdot}8\text{d.}$$

(*a*) Thermal efficiency of combined engine and generator

$$= \frac{3{,}185{,}000}{11{,}125{,}000} \times 100\%$$

$$= 28\ 64\%.$$

(*b*) Efficiency of combined motors and gears

$$= \frac{47{,}520 \times 60}{3{,}185{,}000} \times 100 = 89{\cdot}5\%.$$

(*c*) H.P. at rail $= \dfrac{47{,}520 \times 60}{33{,}000} = 86{\cdot}4.$

$$\therefore \text{ fuel cost per H.P. per hour} = \frac{31\ 8}{86{\cdot}4} \text{ or } 0{\cdot}368\text{d.}$$

Example 6. *A four-cylinder motor-car engine working on the four-stroke cycle has cylinders of* 2 2 *in. bore and* 3 *in. stroke. At normal full speed the engine makes* 2,400 *r.p.m. and the I.H.P. developed is* 14, *when using petrol of specific gravity* 0·75 *and calorific value* 19,000 *B.Th.U. per lb. Calculate*

(*a*) *the mean effective pressure ;*

(*b*) *the full consumption in gallons per hour, assuming a thermal efficiency of* 20% *at normal full speed.*

(*a*) $\text{I.H.P.} = \dfrac{4PALE}{33{,}000}$ or $P = \dfrac{33{,}000 \times \text{I.H.P.}}{4ALE}$

$$= \frac{33{,}000 \times 14}{\pi \times 1{\cdot}1^2 \times 0{\cdot}25 \times 1{,}200 \times 4}$$

$$= 101{\cdot}3 \text{ lb. per sq. in.}$$

(*b*) Energy supplied to engine per hour

$$= 14 \times 33{,}000 \times 60 \times 5 \div 778 \text{ B.Th.U.}$$

since only 1 part in 5 is usefully employed, *i.e.* 20%,

$$= 178{,}100 \text{ B.Th.U.}$$

$$\text{Wt. of petrol supplied per hour} = \frac{178{,}100}{19{,}000} \text{ or } 9{\cdot}374 \text{ lb.,}$$

and since 1 gallon of petrol weighs $10 \times 0{\cdot}75$ lb.

$$\text{Fuel consumption in gallons per hour} = \frac{9{\cdot}374}{10 \times 0{\cdot}75} \text{ or } 1{\cdot}25.$$

Example 7. *A car fitted with a 6-cylinder petrol engine and working on a four-stroke cycle has cylinders of* $2\frac{1}{4}$ *in. bore and piston stroke* 3·94 *in. The top gear ratio is* 4·77 *and the road wheel diameter* 26 *in. At an engine speed of* 3,790 *r.p.m. the mean effective pressure is* 66 *lb. per sq. in. and the fuel consumption is* 2·3 *gallons per hour. Taking the specific gravity of the fuel as* 0·77 *and the calorific value as* 19,500 *B.Th.U. per lb., calculate (a) the I.H.P.; (b) the indicated thermal efficiency; (c) the road speed in m.p.h.; and (d) the mileage per gallon of fuel.*

$$(a)\quad \text{I.H.P.} = \frac{66 \times \pi \times 2{\cdot}25^2 \times 3{\cdot}94 \times 3790 \times 6}{4 \times 12 \times 2 \times 33{,}000}$$

$$= 29{\cdot}69.$$

$$(b)\quad \text{Indicated thermal efficiency} = \frac{\text{heat equivalent of I.H.P.}}{\text{heat to engine per min.}} \times 100$$

$$= \frac{29{\cdot}69 \times 33{,}000 \times 60 \times 100}{2{\cdot}3 \times 7{\cdot}7 \times 19{,}500 \times 778}$$

$$= 21{\cdot}9\%$$

NOTE.—Since the specific gravity of petrol is 0·77 and 1 gallon of water weighs 10 lb., 1 gallon of petrol weighs 7·7 lb.

$$(c)\quad \text{Circumference of road wheel} = \frac{26\pi}{12} \text{ ft.}$$

$$\text{Road wheel speed} = \frac{3790}{4{\cdot}77} \times \frac{60}{1} \text{ revs. per hour}$$

$$= \frac{3790 \times 60 \times 26\pi}{12 \times 4{\cdot}77 \times 5280} \text{ m.p.h.}$$

$$= 60 \text{ m.p.h.}$$

$$(d)\quad \text{Mileage per gallon of fuel} = \frac{60}{2{\cdot}3} = 26{\cdot}1 \text{ miles per gallon}$$

Example 8. *Assuming that the following equation :*

$$2C_6H_{14} + 19O_2 = 12CO_2 + 14H_2O$$

represents the complete combustion of petrol, calculate the minimum quantity of air required per lb. of petrol if air contains 23% by weight of oxygen. The excess air supplied is 50% of the theoretical quantity required for combustion. Find the heat carried off per lb. of petrol used by the exhaust gases at 900° F. and the percentage loss in this way, if the calorific value of the petrol is 19,500 B.Th.U. per lb. Specific heat of exhaust gases = 0·25. Air temperature, 60° F.

Molecular weight of petrol,		$C_6H_{14} = 86$
,, ,, ,,	oxygen.	$O_2 = 32$
,, ,, ,,	carbon dioxide,	$CO_2 = 44$
,, ,, ,,	water,	$H_2O = 18$

From the equation,

$$2C_6H_{14} + 19O_2 = 12CO_2 + 14H_2O,$$

$$2 \times 86 \text{ lb.} + 19 \times 32 \text{ lb.} = 12 \times 44 \text{ lb.} + 14 \times 18 \text{ lb.}$$

$\therefore$ 172 lb. of petrol needs 19×32 or 608 lb. of oxygen for complete combustion.

$\therefore$ 1 lb. of petrol needs $3\frac{23}{43}$ lb. of oxygen.

$3\frac{23}{43}$ lb. of oxygen is contained in $3\frac{23}{43} \times \frac{100}{23}$ lb. of air.

$\therefore$ minimum air required $= \frac{152}{43} \times \frac{100}{23}$ or **15·37 lb. of air.**

Total air supplied $= 15{\cdot}37 + 50\% = 23{\cdot}06$ lb.

Heat carried away per lb. of petrol

$$= (23{\cdot}06 + 1) \times 0{\cdot}25 \times (900 - 60) \text{ B.Th.U.}$$

$$= \mathbf{5052{\cdot}6\ B.Th.U.}$$

$$\text{Percentage loss} = \frac{5052{\cdot}6}{19{,}500} \times 100 = \mathbf{25{\cdot}9.}$$

EXERCISES ON CHAPTER V

Principles of construction and control of internal combustion engines.

1. Describe the four-stroke or Otto cycle.

2. Sketch a section of a small gas engine showing the principal parts.

3. Describe the principles of operation of a gas engine.

4. Show on a sketch the approximate times for valve opening and shutting and ignition, in relation to the position of the crank for a gas engine working on the Otto cycle.

5. Describe the method of governing any internal combustion engine with which you are acquainted.

6. Deal briefly with the fundamental differences between (a) an internal combustion engine and a steam reciprocating engine, and (b) a gas and a Diesel engine. State the relative advantages, in each case, which one engine possesses over the other.

7. Sketch the indicator card of a gas engine with correct timing of valves and ignition.

8. Distinguish between pre-ignition and back-firing. How does the former alter the indicator diagram ?

9. Why is the mechanical efficiency of a gas engine or I.C. engine usually less than that of the reciprocating steam engine ? Define brake thermal efficiency. Which of the engines mentioned in this question has the lower brake thermal efficiency ?

10. Describe the two-stroke cycle as applied to the Diesel engine. Why is a scavenge pump necessary ?

11. Explain briefly how high compression increases the thermal efficiency of the internal combustion engine. State some of the measures adopted to combat the mechanical difficulties entailed. Why is a high compression ratio impossible in a gas engine ?

12. State the functions, and briefly describe, the silencer and anti-fluctuator of a gas engine.

13. Sketch a valve suitable for a gas engine, and show by neat sketches the method of actuating the valve from the half-time cam shaft.

14. Describe the method adopted for cooling any internal combustion engine with which you are acquainted. Give sketches.

15. State the advantages and disadvantages attached to the employment of a high compression ratio in the internal combustion engine.

16. Draw diagrams to illustrate the valve operation in relation to crank and piston positions for a two-stroke Diesel engine. Show clearly these positions for the commencement and completion of fuel injection, combustion, expansion, exhaust, scavenging, compression and power.

17. Sketch an indicator diagram for a two-stroke Diesel engine, and mark on it the duration of the operations mentioned in Question 16.

18. Describe with the aid of a sketch the battery and coil ignition method for producing a spark in the petrol engine.

19. How is an explosive mixture obtained in the petrol engine ? Sketch and describe one form of apparatus employed.

20. What is airless injection? State the function and give particulars of an atomiser.

21. Differentiate between the constant volume and constant pressure cycles. Upon what cycle does the semi-Diesel engine work? Why is the latter engine becoming very popular?

22. Give three different methods of classifying internal combustion engines. Provide examples in each case.

23. Sketch typical indicator diagrams from (*a*) a high compression or Diesel oil engine with combustion at constant pressure, (*b*) a medium compression oil engine with dual combustion, and (*c*) a low compression oil engine with combustion at constant volume. Assume a four-stroke cycle in each case.

24. State the types of gas suitable for use in gas engines, and briefly describe a method of obtaining one of them.

25. What are the methods employed for starting heavy oil engines? What is the meaning of the term "cold starting"?

26. Describe briefly the method of injecting fuel into a heavy oil engine cylinder by air blast. What are the advantages and disadvantages of the method?

27. Give three different methods of classifying heavy oil engines, stating the headings for each type of classification. What advantages do heavy oil engines possess over the light oil engines, *i.e.* those using petrol and paraffin as fuel?

28. Describe briefly, with diagrams, the working of a two-stroke oil engine. (U.L.C.I.)

29. Make a list of the observations which are necessary, and show what calculations have to be made, in carrying out a simple test on an internal combustion engine.

30. Sketch and describe the main features of an indicator suitable for a high speed Diesel engine.

Power and performance of internal combustion engines.

31. A ship consumes for driving purposes 55 tons of oil per day of 24 hours. One pound of oil when burned gives out 10,300 C.H.U. Find how many ft. lb. of energy are available per minute and the horse power this represents. (U.L.C.I.)

32. Make a sketch of the indicator diagram you would expect to obtain from a gas engine working on the Otto cycle.

Find the I.H.P. of such an engine when the mean effective pressure of a working stroke is 73·7 lb. per sq. in., diam. of cylinder 8·5 in., stroke 16 in., revs. per min. 199, explosions per min. 60. (U.L.C.I.)

33. One pound of petrol generates 18,200 B.Th.U. when burned completely. If an engine converts 30% of the heat of combustion into work in the cylinder and its mechanical efficiency is 0·82, what will be the weight of petrol consumed per hour per brake horse power? State what becomes of the remainder of the heat. (U.L.C.I.)

34. Describe the four-stroke cycle of operations of a gas engine, and make a sketch of a typical indicator diagram. The length and area of a gas engine indicator diagram were respectively 3·4 in. and 1·15 sq. in. The diam. of the cylinder was 10 in. and the length of the stroke was 16 in. The number of revolutions and explosions per min. were respectively 180 and 75, and the strength of the spring was 160 lb. per inch movement of the indicator pencil. Find the I.H.P. of the engine.
(U.L.C.I.)

35. The very low value, with airless injection, of 0·358 lb. of shale oil per B.H.P. hour was recorded for a single cylinder engine of 8 in. bore and 11 in. stroke working on the Otto cycle when the speed was 1000 r.p.m. The mean effective pressure was 100 lb. per sq. in. and the mechanical efficiency 78%.

Calculate (a) the indicated horse power,
(b) the brake horse power,
(c) the brake thermal efficiency.

C.V. of oil, 18,200 B.Th.U. per lb.

36. A four-cylinder petrol engine developing 20 B.H.P. at 1060 r.p.m. has cylinders of $3\frac{3}{4}$ in. bore and 5 in. stroke. The mean effective pressure was 91 lb. per sq. in. Calculate the indicated horse power and the mechanical efficiency.

37. Fig. 132 shows an indicator card obtained from a single cylinder gas engine of 5 in. bore and 12 in. stroke at 303 r.p.m. Gas consumption was at the rate of 161·8 cu. ft. per hour when the volume was reduced to N.T.P. Calculate the I.H.P. of the engine and the gas consumption in cu. ft. per I.H.P. hour.

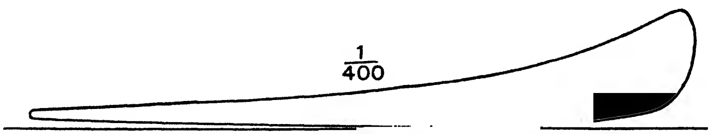


FIG. 132. Indicator card from gas engine.

38. Obtain the mean effective pressure for each of the Diesel engine indicator diagrams shown in Fig. 117, assuming that the spring scale is 280 lb. per sq. in. per inch.

State the difference in procedure in finding the indicated horse power of a two-stroke engine and the four-stroke engine.

39. Fig. 133 shows an indicator diagram taken from an airless injection oil engine of the hot bulb type. The bore and stroke are 7·5 in.

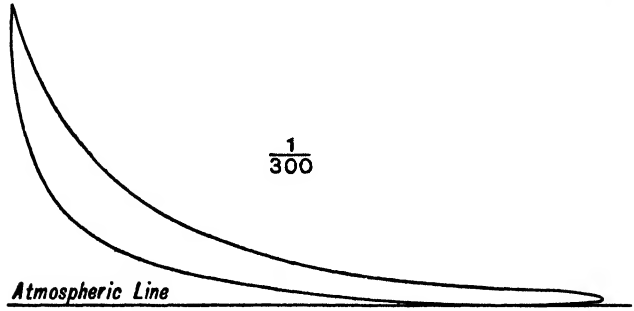


FIG. 133. Indicator card from an airless-injection oil engine.

and 15 in. respectively and the engine speed 260 r.p.m. Calculate (*a*) the mean effective pressure, (*b*) the I.H.P., and (*c*) the mechanical efficiency if the B.H.P. was 11·05.

40. Assuming the power output of an internal combustion engine is reduced by 3% for every 1000 ft. rise above sea-level and 1% for every 5 F. measured above 90° F. in tropical countries, estimate the probable horse power of a 100 H.P. engine (*a*) at 3000 ft. above sea level in a temperate climate, (*b*) at 105° F. at sea-level in the tropics.

41. A four-cylinder, air-cooled aero-engine with cylinders of 118 mm. bore and 140 mm. stroke develops 120 B.H.P. at 2100 r.p.m. and consumes 8·5 gallons of petrol per hour. If the mechanical efficiency is 78%, calculate the mean effective pressure and the fuel consumption in pints per B.H.P. hour.

A 500 B.H.P. Crossley Premier engine on full load test used 0·392 lb. of fuel oil per B.H.P. hour. On changing over to town gas of gross value 500 B.Th.U. per cu. ft. the gas consumption was 19·3 cu. ft. per B.H.P. hour. C.V. of fuel oil was 19,300 B.Th.U. per lb. Compare the performances by converting the consumption of heat energy to B.Th.U. per B.H.P. hour.

43. A gas engine with four cylinders each of 9 in. bore and 13 in. stroke develops 108 B.H.P. at 500 r.p.m. and drives a generator the output of which is 70 kW. If the mechanical efficiency of the engine is 72%, find (*a*) the brake torque, (*b*) the efficiency of the generator, and (*c*) the mean effective pressure for the four cylinders.

44. If in Question 43 the brake thermal efficiency of the engine is 27% and the calorific value of the gas 500 B.Th.U. per cu. ft., estimate the fuel consumption in cu. ft. per hour and cu. ft. per B.H.P. hour.

45. The mean effective pressure for the six cylinders of a four-stroke marine oil engine are respectively 113, 107, 110, 116, 120 and 114 lb. per sq. in. The bore of the cylinders is 22·05 in. and the stroke 39·37 in., while 1,118 B.H.P. is developed at an average speed of 128·9 r.p.m. If 156,500 B.Th.U. are supplied to the engine per minute, calculate (*a*) the indicated horse power, (*b*) the mechanical efficiency, (*c*) the indicated and brake thermal efficiencies.

46. The following mean observations were made during a test on a small gas engine:

Bore, 5 in.; stroke, 12 in.; compression ratio, 4 : 1; r.p.m., 324; mean effective pressure, 59·3 lb. per sq. in.; gas consumption, 2·25 cu. ft. per min. at 60° F. and a pressure of 30 in. of mercury; calorific value of gas, 480 B.Th.U. per cu. ft.; mean brake load at radius of 1 ft. 8 in., 45·4 lb.; 5·1 lb. of cooling water per min. raised 79° F. each minute.

Find the indicated and brake horse powers, the mechanical, brake and indicated thermal efficiencies, and the percentage of heat lost in the cooling water. The number of explosions per minute averaged 162.

47. In a full load test on a stationary single-cylinder Diesel engine, working on the four-stroke cycle with a compression ratio of 15·5 to 1, the following observations were made:

Fuel consumption, 15·75 lb. per hour; R.P.M., 193; mean effective pressure, 99·4 lb. per sq. in.; bore, 11·8 in.; stroke, 18·125 in.; cooling water, 17·6 lb. per min. raised from 14·8° C. up to 54·5° C.; calorific value of fuel, 10,160 C.H.U. per lb. (lower value); brake torque, 959 lb. ft.

Determine the indicated and brake horse powers, the mechanical, indicated and brake thermal efficiencies.

48. Draw up a simple heat balance sheet for the engine of Question 47.

49. A lorry engine with four cylinders, each of 4·5 in. bore and 5 in. stroke running at 1000 r.p.m., consumed 0·52 lb. of petrol per I.H.P. hour. If the mean effective pressure for each cylinder is 90 lb. per sq. in. and the petrol used has a calorific value of 20,000 B.Th.U. per lb. and a specific gravity of 0·78, find (*a*) the indicated horse power, (*b*) the fuel consumption in gallons per hour, (*c*) the indicated thermal efficiency.

During a test on a six-cylinder marine oil engine, working on the four-stroke cycle with a compression ratio of 12·32 to 1, the following data was obtained:

Mean speed, 142·3 r.p.m.; bore (average), 24·41 in.; stroke (average), 51·18 in.; B.H.P., 3020; M.E.P. for six cylinders, 135, 142, 147, 128, 139, 141 lb. per sq. in. respectively; fuel used, 1264 lb. per hour;

C.V., 19,500 B.Th.U. per lb.; cooling water, 1253 lb. per min. raised from 80° F. to 124·8° F.

Draw up a simple heat balance sheet showing the method of disposal of the heat given to the engine.

51. Sludge gas having a calorific value of 680 B.Th.U. per cu. ft. at 60° F. and 30 in. of mercury is used in an engine developing 20 B.H.P. at 450 r.p.m. The composition of the gas by weight is: methane 66%, carbon dioxide 29·7%, nitrogen 4% and oxygen 0·3%. Assuming a brake thermal efficiency of 27%, calculate

(*a*) the probable fuel consumption in cu. ft. per hour,

(*b*) the minimum air for complete combustion of 1 cu. ft. of gas.

52. If benzole has a calorific value of 18,600 B.Th.U. per lb. and a chemical composition of carbon 90·52%, hydrogen 9·02%, calculate the minimum air required for complete combustion per lb. of benzole and also the heat available per lb. of mixture if this minimum air is used to form an explosive mixture in a light-oil engine.

53. In a Diesel locomotive with a direct wheel drive and 12 cylinders each of $20\frac{3}{8}$ in. bore and 17 in. stroke, the crank speed is 420 r.p.m. The engine is single-acting and works on the four-stroke cycle. Calculate the mean effective pressure required if the I.H.P. developed is to be 3500.

If the minimum air required per lb. of fuel is 14 lb., while the air actually used is 2·5 times the minimum, determine the amount of heat carried away in the excess air and in the products of combustion per lb. of fuel if these are at 880° F. Take the air inlet temperature as 60° F. and the specific heats as 0·25 for the products of combustion and 0·24 for air.

54. If the fuel consumption of the locomotive of Question 53 is 1400 lb. per hour, draw up a simple heat balance sheet and estimate the percentage of the total heat supplied which has been lost in the cooling of the engine. C.V. of fuel is 19,500 B.Th.U. per lb.

55. The four cylinders of a car engine rated at 11·9 H.P. have a bore of 69·5 mm. and a stroke of 106 mm., and the engine works on the four-stroke cycle. The top gear ratio is 4·71 and the road wheel diameter 26 in. When the engine is running at 3600 r.p.m. the mean effective pressure is 114 lb. per sq. in. and the fuel consumption 2·11 gallons per hour. If the calorific value of the petrol is 19,500 B.Th.U. per lb. and the specific gravity 0·76, determine

(*a*) the indicated horse power,

(*b*) the indicated thermal efficiency,

(*c*) the brake thermal efficiency if the B.H.P. is 42,

(*d*) the road speed in miles per hour,

(*e*) the mileage per gallon of fuel.

56. Fig. 134 shows an indicator card taken from a marine oil engine *working on the four-stroke dual cycle.* The cylinder diameter is 22·5 in.,

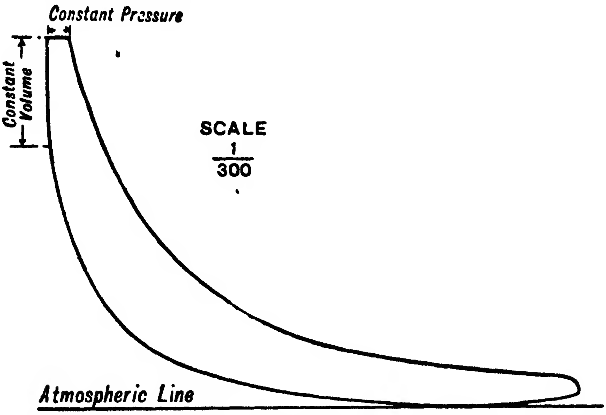


FIG. 134. Indicator card from a cold starting, medium compression, oil engine.

the piston stroke 37·5 in., and the mean speed 126·9 r.p.m. The mechanical efficiency of the engine was stated to be 73·3%.

Obtain the following :

(*a*) the maximum compression pressure,
(*b*) the maximum pressure reached during combustion,
(*c*) the mean effective pressure,
(*d*) the indicated and brake horse powers.

If the spring for the indicator diagram shown in Fig. 134 were $\frac{1}{360}$, find the maximum gauge pressure in lb. per sq. in. reached during combustion.

57. Calculate the mean effective pressure for the nine cylinders of a single-acting two-stroke Diesel engine developing 7,500 B.H.P. if the mechanical efficiency is 72%. The cylinders have an average bore of 33·8 in. and a stroke of 59 in., while the engine speed is 96 r.p.m. What is the indicated thermal efficiency if the fuel consumption is 3340 lb. per hour? C.V. of fuel oil 10,500 C.H.U. per lb.

CHAPTER VI

ELECTRIC CURRENTS AND THEIR EFFECTS

Electrical energy and its control—Effects produced by a passing electric current—Chemical effect—The electric circuit—Heating effect

It has been shown that the energy possessed by a fuel may be converted into heat energy, and this heat energy to mechanical energy. The latter may then be used to drive a generator or dynamo, which in turn provides electrical energy for the multitude of purposes for which it can be used, both close at hand or at a distance.

Electrical energy is generally regarded as being conveyed by a **quantity** of electricity which must be forced along a conductor against some form of **resistance** by a **pressure**, and this electricity will do work in passing or overcoming the resistance. The passage of this electricity or **current**, as it is called, can be likened to the conveyance of hydraulic energy by the flow of water under pressure through a pipe against the resistance due to friction and against the back pressure due to hydraulic machinery. This comparison of the passage of a current with the flow of water is often referred to as the hydraulic analogy.

Energy in the form of electrical energy can be easily transmitted from point to point, often over great distances, and this energy can be tapped off conveniently at any stage in its transmission and readily converted into heat, light, mechanical or sound energy by means of suitable apparatus or plant. Electrical energy possesses great advantages over other forms of energy in the ease with which it can be transmitted or transferred from place to place.

At this stage, conductors may be regarded as being used to convey the electricity, or allow the current to flow; and insulators prevent its loss in directions other than the one desired.

Conductors and insulators. Almost every material will conduct electricity, but some offer very great resistance to its flow. Those materials offering low resistance are called good conductors, as, for example, metals, particularly silver, copper, aluminium, steel and iron, in the order given. Materials such as rubber, mica, paper, cotton, porcelain, asbestos, enamel, resin and glass are called insulators, because they are very poor conductors and allow practically no flow of electricity. However, resistance to the flow of electricity depends not only on the material, but on its temperature and shape. In practice, the choice of a conductor or insulator also depends upon first cost, resistance to corrosion, mechanical strength and in some cases on the ornamental character of the substance.

Effects of a passing current. When a current flows through an electric circuit containing various kinds of liquid and solid conducting material, it is found that there is a loss of electrical energy, and this when converted into heat, chemical and magnetic energy shows itself in the production of one or more of three effects, namely, (*a*) the heating, (*b*) the chemical, and (*c*) the magnetic effect. Usually special apparatus is necessary to convert electrical energy to light, sound and mechanical energy as exemplified by lamps, buzzers and motors respectively.

Frequently when passing through liquid or gaseous conductors. chemical actions take place.

The chemical effect. Electrolysis. In the passage of an electric current no chemical action will take place with a metal conductor, but if part of the circuit consists of a liquid conductor or **electrolyte** such as dilute sulphuric acid and the current flows through the acidulated water between two platinum wires or pieces of foil to serve as **electrodes**, a chemical action takes place as well as a rise of temperature. Ultimately, in the case of water and sulphuric acid, hydrogen is given off at one electrode called the **cathode**, where the current leaves the electrolyte, and oxygen is given off at the **anode**, where the current enters the electrolyte. Perfectly pure water, pure sulphuric and hydrochloric acids are very bad conductors. Good liquid electrolytes are common salt solution and solutions of sodium, copper and chromium sulphates and zinc and copper cyanides. It should be noticed that the hydrogen and oxygen evolved by the

passage of the electric current through acidulated water are the constituents of water. When solutions of salts are used as electrolytes, the metallic part is generally released at the cathode and the remainder at the anode, where it enters into combination with the solution or breaks up still further.

Faraday found that the mass of substance liberated from an electrolyte by this process, which is called **electrolysis**, is proportional to (1) the total quantity of electricity passing through the electrolyte, (2) to a quantity known as the chemical equivalent weight of the substance liberated. The **chemical equivalent** of an element may be defined at this stage as the weight of element which will combine with or displace from a compound, one part by weight of hydrogen.

If copper sulphate solution be substituted for the acidulated water, then copper becomes deposited on the cathode as a thin layer. With silver nitrate as an electrolyte, silver is deposited on the cathode and this is used as a standard and accurate means for measuring the strength of a current.

A **coulomb** is the unit of quantity of electricity and is that quantity which will cause a deposition of 0·001118 gram of silver when it passes through a solution of silver nitrate.

The practical unit of current is called the ampere, abbreviated to amp. or A. The **international ampere is the unvarying current which when passed through a solution of silver nitrate in water deposits silver at the rate of 0·001118 gram per second.**

This process, whereby metal is deposited on the cathode by the passage of a suitable electric current, through a carefully selected electrolyte, is termed **electroplating**, and it is used widely industrially, as a means of preventing corrosion, for electrotyping, and for the repair of worn parts as well as for decorative work. Copper has been successfully deposited on glass in the making of parabolic reflectors for projectors. For chromium plating the electrolyte consists mainly of chromic acid solution, with a little chromic carbonate and sulphate added, kept at a temperature of from 40° to 50° C., with a current of from 100 to 200 amperes passing per square foot of surface to be coated. The voltage of the current is about 8 volts.

EXPT. 35. **Electrolysis of water.**

OBJECTS. (1) *To decompose water electrically into its two constituents, hydrogen and oxygen.*

(2) *To estimate the quantity of each gas, by volume, constituting the water.*

APPARATUS. Arrange an inverted funnel as shown in Fig. 135 and nearly fill it with water to which a little sulphuric acid has been added. Fill the test tubes similarly and invert them as shown over the platinum electrodes. Join the electrodes to the terminals of an accumulator and allow the current to flow for some time. It will be noticed that one test tube accumulates gas at twice the rate of the other, and this is on the side of the negative terminal or cathode. Cut off the current, place the thumb over the end of the cathode tube and invert it. Test the gas for hydrogen by igniting it and noticing the pale blue flame. Repeat the process with the anode tube, but this time insert a glowing splint into the gas. The splint will ignite, thus indicating the existence of oxygen which stimulates combustion.

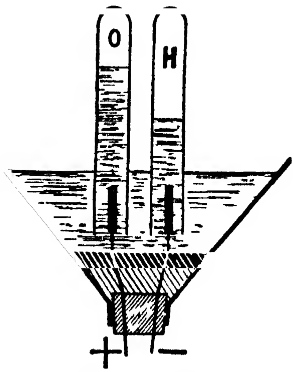


FIG. 135. Electrolysis of water.

CONCLUSIONS. The passage of an electric current through slightly acidulated water will cause decomposition of the water into oxygen and hydrogen, in a volume relation of two parts hydrogen to one part oxygen

NOTE.—*Water which is pure is a very poor conductor of electricity, so that it is necessary to acidulate the water to bring about a ready flow of current.*

EXPT. 36. **Chemical effect of a current.**

OBJECT. *To study the effect of a current passing between two platinum poles immersed, but separated, in a solution of copper sulphate.*

METHOD OF PROCEDURE. Pass two conductors through the cork of a large test tube and terminate each conductor with a piece of platinum wire. Half fill the test tube with a solution of copper sulphate and immerse the platinum in the solution. Join the other ends of the conductor to the terminals of an accumulator and allow the current to pass for a short time. Notice (*a*) what happens to each of the platinum poles, (*b*) distinguish the cathode by the deposit of copper coated upon it, (*c*) note carefully the effect on the other pole or anode.

CONCLUSIONS. The passage of an electric current through a solution of a metallic salt will cause a decomposition of this salt with

a deposit of the metal element on the cathode and a deposit of free gas, in this case oxygen, upon the anode.

The weight of metal (or hydrogen) deposited on the cathode by a current of 1 ampere in 1 second is called the **electro-chemical equivalent of the metal** (or hydrogen).

There is always a change of energy in the passage of the current of electricity through solid, liquid or gaseous conductors which is dissipated as heat. It is found that the greater the cross-sectional area available for the passage of the current and the shorter the path or length of the conductor the less the energy lost in this way. This opposition to the flow of current is called the resistance of the conductor; the resistances of different substances must be compared without the complication of variation in shape. What is called the **specific resistance**, or the resistance to the flow of current from one face of a unit cube to the opposite face, for different materials, has been measured and tabulated. Specific resistance is measured in ohms per inch or per centimetre cube, where the **ohm** is the practical unit of resistance (see p. 292).

The **international ohm is the resistance offered to a constant electric current by a column of mercury 106·3 cm. in length, of unvarying cross-section, weighing 14·4521 grams and at a temperature of 0° C.**

In the same way as a head or pressure of water is necessary before water is made to flow along a pipe and operate hydraulic machines, so an electrical pressure, potential or force is necessary to maintain a flow of electrical energy or a current along a conductor against a resistance and operate electrical appliances. This force or pressure is sometimes called **electromotive force** and abbreviated to **e.m.f.**

Electrical pressure or e.m.f. is measured in practice by **the international volt, a pressure which, on being steadily applied to a conductor of resistance 1 ohm, will produce a current of 1 ampere.**

Sometimes the term, "applied potential difference" (p.d), is used in the place of e.m.f.

Production of an e.m.f. An e.m.f. can be produced by mechanical means by employing a dynamo or generator of electricity in which mechanical energy is converted into electrical energy. This method is dealt with in more detail later, p. 336. In addition, an e.m.f. can be produced by chemical means.

The generation of electrical energy from chemical energy is accomplished by means of the **voltaic or primary cell**, the invention of which was due to Volta. The primary cell is very suitable for the production of small electric currents for intermittent use, as in telegraphy, telephony and bell operation.

In its simplest form a voltaic cell consists of two dissimilar metal plates or rods immersed in some conducting liquid in which chemical action takes place, such as dilute sulphuric acid, shown in Fig. 136. Copper and zinc plates are generally used, and the direction of flow of the current is from the copper to the zinc in the external circuit. Ampère's rule (see p. 308) may be used to detect this current, and the direction in which it is flowing, with the aid of a compass needle. When the current is flowing zinc sulphate is formed and bubbles of hydrogen gas accumulate on the copper plate, a phenomenon known as **polarisation**, and this hydrogen tends to set up a reverse current, which after a time so interferes with the action of the cell that the original current may eventually cease altogether, if the bubbles are not removed. Even when the external circuit is opened the zinc is still slowly eaten away by acid action, and this **local action** is wasteful. It can be lessened by coating the zinc with mercury, which forms a protective amalgam but does not interfere with the action of the cell.

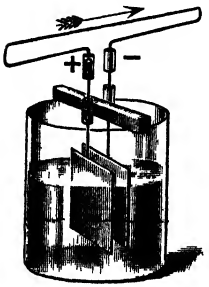


FIG. 136. A simple voltaic cell.

The force which maintains the **potential difference** (p.d.) between the two plates is called the electromotive force (e.m.f.) of the cell. The e.m.f. of the cell shown is approximately 1 volt. In the Leclanché cell, the voltage of which is 1·43 volts (Fig. 137), the copper plate is replaced by a carbon rod surrounded by a mixture of graphite and manganese dioxide contained in a porous pot. The manganese dioxide is rich in oxygen and combines with the hydrogen, which would otherwise form on the carbon rod and cause polarisation. Sal-ammoniac dissolved in water serves as the liquid conductor. A form of Leclanché dry cell to render it portable is made, in which the sal-ammoniac is supplied in paste form, instead

of as a strong solution in water. The Leclanché cell is only suitable for intermittent work, since the manganese dioxide only absorbs the hydrogen slowly, and continual use soon produces polarisation. Another common form of voltaic cell is the Daniell cell. The Weston or Cadmium cell and the Clark cell are examples of standard cells: the e.m.f. of these is specified as constant, the former giving 1·0183 volts at 20° C. and the latter 1·434 volts at 15° C.

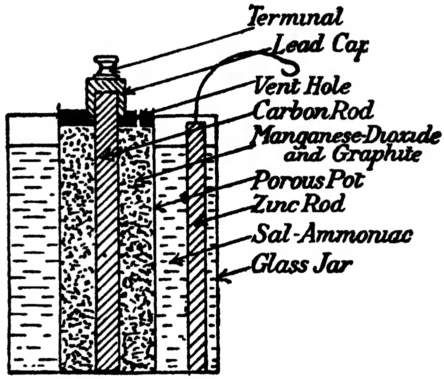


Fig. 137. Leclanché cell.

Expt. 37. **The construction of a simple cell.**

Object. *To show that an electric current flows between two plates, respectively of copper and zinc, which are kept separate in a dilute solution of sulphuric acid.*

Method of procedure. Prepare two plates, one of copper and the other of zinc which has been previously rubbed over with a little mercury. Immerse these plates so that they are kept apart in

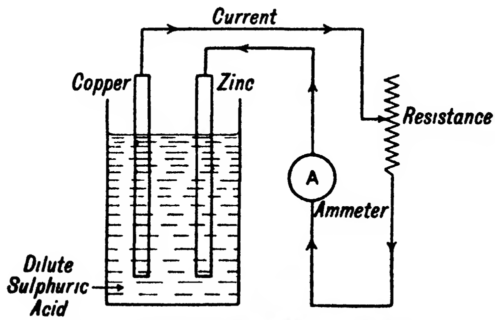


Fig. 138. Simple cell a[illegible] external circuit.

a solution of sulphuric acid. Connect the plates by means of wires and terminals through a resistance and an ammeter (Fig. 138). The

ammeter will then show that a current is passing through the wire between the copper and the zinc. This arrangement is the simplest form of what is known as a primary cell.

Storage of electricity in the form of chemical potential energy. With a voltaic or primary cell, as just described, a chemical reaction or series of reactions is made use of in the production of an electric current, and restoration of the battery can be accomplished by renewal of the electrolyte and electrodes. In the case of the **secondary or storage cell, or accumulator,** the change of chemical to electrical energy is reversible, and by applying an electric current to such a cell the chemical actions which take place in the generation of a current are reversed, and the chemical substances restored to their original condition.

The two principal types of accumulator are the lead-acid and the nickel-iron-alkali cell. With the former the chemical processes involved are concerned with the changes which metallic lead and its compounds undergo in dilute sulphuric acid by the action of an electric current. The small spaces in the grids forming the positive and negative plates of the cell are filled with litharge or red lead or a mixture of the two made into a stiff paste with sulphuric acid and water. As a rule the negative grid is lighter than the positive, as it is less subject to corrosion, and both are made of lead with 7% of antimony. Before use, the plates have to be "formed" by the passage of an electric current while they are immersed in dilute sulphuric acid, to reduce the paste on the negative plate to metallic lead and to oxidise that on the positive to lead peroxide. In this condition the battery is said to be charged. During discharge, both the peroxide on the positive and the lead on the negative become converted into lead sulphate, with water added to, and sulphuric acid removed from, the electrolyte. When again charged the chemical action is reversed, and the cell is fully charged when the plates regain their original state. If a current continues to be passed, gassing will occur, free hydrogen appearing at the cathode or negative plate and oxygen at the positive. The fully charged state is also determined by the density of the electrolyte, which varies from 1·2 to 1·3 according as the discharge rate is to be low or high.

An accumulator is charged by sending a current from the positive to the negative plate through the electrolyte. During discharge the flow is always regarded as being from the positive to the negative plate through the external circuit.

The electric circuit. Current will only flow if there is a *complete* ring or loop of conductors leading from one terminal of the generator to the other. This external loop or ring of conductors is called the external circuit, and a part of the e.m.f. produced by the chemical energy of the cell is utilised in causing a flow of electricity in the external circuit and a part in forcing the current through the electrolyte of the cell itself.

A study of the laws appertaining to the various forms of simple electric circuits will now be commenced.

Power in a circuit and unit of power. If in a circuit a pressure of 1 volt is causing a flow of current at the rate of 1 ampere (or 1 coulomb per second), then this rate of flow of electrical energy or power is called 1 **watt.**

$\therefore$ Work done per second = power expended in watts
= current in amperes × pressure in volts.

The watt is too small a unit of power for many purposes, so that a unit called the **kilowatt** which equals 1000 watts and written kW (see p. 51) is more usually employed.

746 watts are equivalent to 1 horse power.

The standard unit of electrical energy, called the Board of Trade unit (B.T.U.). is a supply of 1 kilowatt maintained for 1 hour. This supply is called the kilowatt-hour (kWh). It is equivalent to 1·340 horse power hours, or alternatively 0·746 kilowatt hour is equivalent to 1 horse power hour. The student should distinguish carefully between B.T.U. and B.Th.U., or British Thermal Unit.

With electrical units the prefixes, meg(a) = a million times, micr(o) = a millionth, kilo = a thousand, and milli = a thousandth are frequently used.

Examples. Megohm = 1 million ohms = 10^6 ohms.
Microvolt = 1 millionth of a volt = 10^{-6} volt.
Milliampere = 10^{-3} ampere.
Kilowatt = 1000 watts.

Example 1. *Calculate the number of horse power hours and ft. lb. which are equivalent to 1 kilowatt hour, that is, 1 B.T.U.*

$$1 \text{ kWh} = 1 \text{ kilowatt hour} = 1 \text{ B.T.U.} = \tfrac{1000}{746}$$
$$= \mathbf{1{\cdot}3403 \text{ horse power hours.}}$$
$$= 1{\cdot}3403 \times 33{,}000 \times 60$$
$$= \mathbf{2{,}653{,}800 \text{ ft. lb.}}$$

Example 2. *Find the necessary current to be supplied to a motor of* 20 *H.P. when the supply is at* 400 *volts.*

$$20 \text{ H.P.} = 20 \times 746 = 14{,}920 \text{ watts.}$$
$$\text{Watts} = \text{volts} \times \text{amperes.}$$
$$14{,}920 = 400\, I.$$
$$\therefore\ I = \mathbf{37{\cdot}3 \text{ amperes.}}$$

NOTE.—A dynamo receives mechanical energy and converts it to electrical energy, whereas a motor receives electrical energy and converts it to mechanical energy. Thus the dynamo gives out electrical energy and the motor mechanical energy.

Ohm's law. This law states that the continuous current I flowing in a closed circuit is proportional to the applied potential difference E, such that $\frac{E}{I}$ is a constant. This constant is called the resistance R of the circuit, and expressed algebraically the law is $R = \frac{E}{I}$. If, as is usually the case, the temperature rises, causing an increase of resistance, then E must be increased to maintain I at the same value. Ohm's law is not strictly true during transient periods, such as sudden stoppage or starting of currents, a condition not considered here but it is true for instantaneous values.

The relations between I, E and R can also be expressed algebraically as $E = I \,.\, R$ or $I = \frac{E}{R}$. In the latter case I varies directly as the pressure E and inversely as the resistance of the circuit. Both these forms are extremely useful in application, as when two of the quantities are known, the third can always be found. When a known current is passing through a circuit of known resistance a definite pressure or electro-motive force (e.m.f.) is required, and this e.m.f. is also known as the difference of potential or voltage drop.

Example 1. *Find the resistance of and the current passing through an electric lamp on a 240 volt supply consuming 100 watts and giving out 90 candle power.*

$$P = \text{watts} = \text{volts} \times \text{amperes} = EI.$$

$$\therefore\ I = \frac{P}{E} = \frac{100}{240} = \mathbf{0{\cdot}42\ amp.}$$

By Ohm's law, $R = \dfrac{E}{I} = \dfrac{240}{0{\cdot}42} = \mathbf{576\ ohms.}$

NOTE.—If the resistance of the lamp exceeds 576 ohms, then the lamp will not take 0·42 ampere, that is assuming the pressure remains constant, and therefore the lamp will not give out the required candle power. On the other hand, if the resistance is less than 576 ohms, the lamp will take more than 0·42 ampere, and the filament of the lamp will not last as long.

Example 2. *A small water boiler consumes 2400 watts on a 240 volt supply. What current is necessary? Also what must be the electrical resistance of the heating elements of the boiler?*

$$\text{Amperes} = \frac{\text{watts}}{\text{volts}} = \frac{2400}{240} = \mathbf{10\ amperes.}$$

By Ohm's law, $R = \dfrac{E}{I} = \dfrac{240}{10} = \mathbf{24\ ohms.}$

Resistance in generators and cells. Generators and cells themselves set up an **internal resistance** to the flow of an electric current when they form part of an electric circuit, and this internal resistance has an important effect on the efficiency of electric circuits generally. In the case of the voltaic cell the resistance of the liquid, plates and connections forms the internal resistance. With series and shunt dynamos the internal resistance includes that of the armature and field coils. The resistance of the circuit external to the terminals of the generator is called the **external resistance.** Generators, conductors, machines, etc., can be grouped in many different ways, and it is important to be able to determine how this grouping affects the resistance to the flow of electricity.

Control of the current in electric circuits. Conductors may be arranged in (1) **series,** (2) **parallel** or (3) **a combination of series** and **parallel,** and in so doing the current flowing in any one branch or part can be controlled by varying the resistance.

Ohm's law holds not only for any portion of a continuous current

circuit, but for the whole circuit. The e.m.f. available is used in forcing the current around the circuit, and should a portion of the circuit be absolutely uniform the drop of electrical pressure along it will be uniform ; or the potential difference between the ends of equal lengths will be the same.

Specific resistance. If a conductor of unit cross-sectional area and unit length be taken, the resistance in ohms set up to the flow of electricity is called the specific resistance or **resistivity** of the material of the conductor, and is usually denoted by the Greek letter ρ. Sometimes the resistivity of a material is defined as the resistance between two opposite faces of unit cube of the material. Since the resistance alters with the temperature, the latter must always be specified. The units of length usually adopted are the inch and the centimetre.

A conductor of 8 units of length will have a potential difference 8 times greater between its ends, and set up 8 times the resistance as compared with one of unit length. If the cross-section is halved the current density must be twice as great, and the resistance is doubled. Therefore to find the resistance of a conductor, ρ is multiplied by the length l and divided by the area a, or $R=\frac{\rho l}{a}$.

Material. Metals pure and annealed	Specific resistance at 0° C.		Mean temp. coefficient between 0 and 100° C. or 32 and 212° F.	
	Microhms per cm. cube	Microhms per in. cube	per 1° C.	per 1° F.
Silver - -	1·468	0·5781	0·004	0·0022
Aluminium -	2·665	1·049	0·00435	0·00242
Copper - -	1·561	0·6146	0·00428	0·00238
Nickel - -	6·935	2·730	0·0062	0·00344
Mercury - -	94·07	37·03	0·001	0·000556
Iron - - -	9·065	3·569	0·00625	0·00347
Arc lamp carbon	7000·0	2756·	0·0005	0·00028

In the above table the specific resistance and also the mean temperature coefficients are given for a few materials. The mean temperature coefficient α will allow for the specific resistance being calculated for temperatures t between 0 and 100° C., since

$$R_t = R_0(1+\alpha t) \text{ approximately.}$$

R_t and R_0 are the resistances at t° C. and 0° C. respectively.

Example 1. *Determine the resistance of an inch cube of copper at* 50° *C.* $\alpha = 0{\cdot}00428$.

$$R_0 = \rho\frac{l}{a}, \text{ where } \rho = \frac{1{\cdot}561}{10^6} \text{ ohm, } l = 2{\cdot}54 \text{ cm., } a = 2{\cdot}54^2$$

$$= \frac{1{\cdot}561}{10^6} \times \frac{2{\cdot}54}{2{\cdot}54^2} = \frac{0{\cdot}6146}{10^6} \text{ ohm or } 0{\cdot}6146 \text{ microhm.}$$

$$R_t = R_0(1+\alpha t) = 0{\cdot}6146(1+0{\cdot}00428 \times 50) = \mathbf{0{\cdot}746 \text{ microhm.}}$$

Example 2. *A steel cored aluminium cable consists of* 19 *galvanised steel wires of* $\frac{1}{8}$ *in. dia. surrounded by* 18 *aluminium wires of the same size. The steel core is provided to give strength for overhead work, and is ignored in calculations for resistance and conductivity. What is the resistance of the aluminium per* 1000 *ft. at* 0° *C.?*

$$R = \rho\frac{l}{a}, \quad \text{where} \begin{cases} \rho = 2{\cdot}665 \text{ microhms per cm. cube,} \\ l = 12{,}000 \times 2{\cdot}54 \text{ cm.} = 30{,}480 \text{ cm.,} \\ a = 18 \times \frac{\pi}{4} \times \left(\frac{1}{8}\right)^2 \times 2{\cdot}54^2 = 1{\cdot}425 \text{ sq. cm.} \end{cases}$$

$$= \frac{2{\cdot}665 \times 30{,}480}{1{\cdot}425 \times 10^6}$$

$$= \mathbf{0{\cdot}0570 \text{ ohm.}}$$

Resistance in series. A generator or cell driving a current through an external circuit of resistance R_e and overcoming its internal resistance R_i provides an example of resistances in series, since the same current I is flowing in the two parts. If E is the e.m.f. causing the current to flow, the voltage drop internally and externally will be IR_i and IR_e respectively. Therefore

$$E = IR_i + IR_e.$$

If R is the total resistance of the circuit, and since Ohm's law is true for the whole circuit and the part, then

$$E = IR = IR_i + IR_e \text{ or } R = R_i + R_e.$$

or **total resistance = sum of separate series resistances.**

In the above, IR_i is the e.m.f. required to drive a current through the cell. The potential difference (p.d.) across the terminals of the cell available for forcing a current through an external circuit is thus IR_e or p.d. $= E - IR_i = IR_e$. When no current is flowing then e.m.f. = p.d , and the cell is said to be on **open circuit.**

Example 1. *Three electric lamps of resistances* 1000, 1000 *and* 400 *ohms respectively are connected in series and the current flowing is* 0·2 *ampere. What is the p.d. across each lamp and across the three ?*

p.d. across 1000 ohm lamps $= E = IR = 1000 \times 0{\cdot}2 =$ **200 volts.**

,, ,, 400 ,, ,, $= 400 \times 0{\cdot}2 =$ **80 volts.**

Total p.d. $= 200 + 200 + 80 = (2400 \times 0{\cdot}2) =$ **480 volts.**

Example 2. *A cell has an e.m.f. of* 1·8 *volts and an internal resistance of* 0·15 *ohm. Determine the* p.d. *across the terminals and the current when connected to an external circuit of* (*a*) 2 *ohms and* (*b*) 2000 *ohms.*

(*a*) Total resistance $= 0{\cdot}15 + 2 = 2{\cdot}15$ ohms.

$$\text{Current} = I = \frac{E}{R} = \frac{1{\cdot}8}{2{\cdot}15} = \mathbf{0{\cdot}837\ amp.}$$

$$\text{Terminal p.d.} = IR_e = E - IR_i = 0{\cdot}837 \times 2 = \mathbf{1{\cdot}674\ volt.}$$

(*b*) Total resistance $= 2 + 2000 = 2002$ ohms.

$$\text{Current} = I = \frac{E}{R} = \frac{1{\cdot}8}{2002}$$

$$= \mathbf{0{\cdot}0008993\ amp.}\ \text{or}\ 0{\cdot}8993\ \text{milliamp.}$$

$$\text{Terminal p.d.} = IR_e = 0{\cdot}0008993 \times 2000 = \mathbf{1{\cdot}7986\ volt.}$$

It should be noticed that the greater the resistance of the external circuit the more nearly do the p.d. and e.m.f. have the same value.

Example 3. *A certain uniform wire* 105 *cm. in length and having a resistance of* 1·2 *ohms is connected in series with an adjustable resistance and a single storage cell. If the internal resistance of the cell is* 0·085 *ohm and its e.m.f. is* 2 *volts, what must be the value of the adjustable resistance so that the potential drop along the wire may be* 0·01 *volt per cm. ?*

(U.L.C.I.)

Let x ohms be the magnitude of the adjustable resistance and I the current in the circuit.

Total resistance $= 1{\cdot}2 + 0{\cdot}085 + x = 1{\cdot}285 + x$ ohms.

Applying Ohm's law to the whole circuit, $I = \dfrac{E}{R} = \dfrac{2}{1{\cdot}285 + x}$ . ...(1)

Potential difference between ends of wire $=105\times 0{\cdot}01=1{\cdot}05$ volts.

Applying Ohm's law to the wire portion of the circuit,

$$I=\frac{E}{R}=\frac{1{\cdot}05}{1{\cdot}2}. \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equating (1) and (2), $I=\dfrac{2}{1{\cdot}285+x}=\dfrac{1{\cdot}05}{1{\cdot}2}$.

Cross multiply, $1{\cdot}349+1{\cdot}05x=2{\cdot}4$,

$$x=1 \text{ ohm.}$$

Resistance in parallel. When a current divides temporarily to pass along several conductors at the same time, the conductors are said to be in parallel.

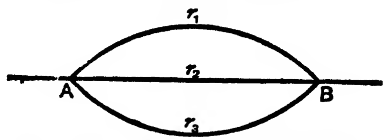


FIG. 139. **Resistances in parallel.**

Let E and R be the p.d. and total resistance between A and B.

Then $I=i_1+i_2+i_3$, and as by Ohm's law $I=\dfrac{E}{R}$, $i_1=\dfrac{E}{r_1}$, etc.,

$$\frac{E}{R}=\frac{E}{r_1}+\frac{E}{r_2}+\frac{E}{r_3},$$

then, dividing each fraction by E, $\dfrac{1}{R}=\dfrac{1}{r_1}+\dfrac{1}{r_2}+\dfrac{1}{r_3}$.

That is,

the reciprocal of the total resistance is equal to the sum of the reciprocals of the separate resistances.

This law is true for any number of resistances in parallel. The reciprocal of the resistance of a conductor is termed the **conductivity.**

In a continuous current public supply circuit, in order to reduce the total resistance to a minimum, the various heaters, lamps and motors supplied with power are connected in parallel across the outgoing lead and the return lead to the dynamo. By measuring the p.d. across the terminals of the dynamo and the total current in the external circuit the product of the readings will give the power in watts supplied to the external circuit.

Example 1. *Four lamps, each of resistance* 500 *ohms, and an electric heater of resistance* 3000 *ohms are connected in parallel across the terminals of a dynamo. What is the equivalent resistance ?*

$$\frac{1}{R}=\frac{1}{500}\times 4+\frac{1}{3000}=\frac{25}{3000} \text{ or } R=\frac{3000}{25}=\mathbf{120\ ohms.}$$

Example 2. *Four Daniell cells are connected in parallel, that is, all their positive terminals connected and all their negative terminals connected to make one positive and one negative terminal, to an external resistance of* 1 *ohm. If the e.m.f. and internal resistance of each cell are respectively* 1·15 *volt and* 0·9 *ohm, find the current flowing in the external circuit.*

Total e.m.f. $=1{\cdot}15$ volt. Total resistance of battery $=R_i$.

Then $\dfrac{1}{R_i}=\dfrac{1}{0{\cdot}9}+\dfrac{1}{0{\cdot}9}+\dfrac{1}{0{\cdot}9}+\dfrac{1}{0{\cdot}9}=\dfrac{4}{0{\cdot}9}$; $\therefore\ R_i=0{\cdot}225$ ohm.

The current in the four cells = current in external circuit

$$=\frac{E}{R_i+R_e}=\frac{1{\cdot}15}{1{\cdot}225}=\mathbf{0{\cdot}939\ amp.}$$

Example 3. *If the four cells of Example 2 are connected in series, that is, the positive terminal of one cell connected to the negative of the next, with the same external resistance, find the current in the whole circuit.*

Total e.m.f. $=1{\cdot}15\times 4=4{\cdot}6$ volt.

$R_i=4\times 0{\cdot}9=3{\cdot}6$ ohm. $R_e=1$ ohm.

Then $$I=\frac{E}{R_i+R_e}=\frac{4{\cdot}6}{4{\cdot}6}=\mathbf{1\ amp.}$$

Note.—*The connection of cells in series provides a higher e.m.f while the connection in parallel lowers the total resistance and tends to increase the current.*

Example 4. *Three Daniell cells connected in parallel are joined in series with a bichromate cell of e.m.f.* 2 *volts and internal resistance* 0·25 *ohm. What is the combined e.m.f. and resistance of the battery ? Use data from Example* 2.

Total e.m.f. $=1{\cdot}15+2=\mathbf{3{\cdot}15\ volts.}$

$$R_i=0{\cdot}25+\frac{1}{3\times\frac{1}{0{\cdot}9}}=0{\cdot}25+0{\cdot}3=\mathbf{0{\cdot}55\ ohm.}$$

A shunt. It is common practice in the use of electrical instruments to connect to the instrument a resistance in parallel which is known as a shunt. This resistance serves to divide the current with the result that a certain fraction of the current passes through the instrument and the remainder through the resistance or shunt.

Example. *A strong current is to be measured by passing $\frac{1}{1000}$th part of the current through a galvanometer and the remainder through a shunt or resistance in parallel. If the resistance of the galvanometer is* 80 *ohms, find that of the shunt.*

If total current is $1000i$, $999i$ will pass through the shunt. Let E p.d. across galvanometer and shunt.

Applying Ohm's law to each part, $\frac{E}{80}=i$, $999i=\frac{E}{x}$, where x = resistance of shunt.

$$\text{Total current} = 1000i = i + 999i.$$

$$1000 \times \frac{E}{80} = \frac{E}{80} + \frac{E}{x},$$

or

$$x = \tfrac{80}{999} \text{ ohm}.$$

NOTE.—*If a shunt is to be provided so that $\frac{1}{n}$th of the whole current passes through the instrument, then*

$$\textit{resistance of shunt} = \frac{1}{n-1} \times \textit{resistance of instrument.}$$

Heating effect of a current. About 1841 James Joule showed that *the heat H generated in a wire is proportional to (a) the square of the current I passing through it, (b) to the resistance R of the wire, and (c) the time t during which the current is maintained.*

This can be expressed as H varies as I^2Rt or $H = kI^2Rt$, where k is a constant equal to 0·2388, if H is expressed in gram calories, and I, R and t are respectively in amperes, ohms and seconds. The quantity I^2Rt will then be in **watt-seconds** and a watt-second is called **a joule.** It is found that 1 joule of energy is equivalent to 0·2388 gram calorie.

Expressed in another way—

$$1 \text{ watt} = 1 \text{ joule per sec.}$$

and 4·187 joules are equivalent to 1 gram calorie.

Conversion from gram calories to B.Th.U. may be effected by using the relation 1 B.Th.U. = 251·996 gram calories.

This production of heat during the passage of a current is always present to a greater or lesser extent. It is very undesirable in machines, and is avoided, as far as possible, in the case of the windings of generators or motors. In other cases, as with electric fires, cookers, lamps, etc., the production of heat is deliberate, and the heating coils have to possess sufficient resistance to give the heat energy desired without burning. The heating effect of a current can be used in its measurement, and also in the protection of the apparatus in electric circuits when fuses are inserted. A fuse will safely carry the normal current, but should the resistance of the circuit decrease through some fault such as short circuit, and the current increase in value to a dangerous degree, the strong current passing through the fine fuse wire will quickly melt the wire and break the circuit.

Example 1. *Find the heat generated in B.Th.U. when a current of* 4 *amperes flows through a resistance of* 100 *ohms for* 10 *minutes. If* 75% *of this heat is used to raise some water through* 150° *F., find the weight of the water.*

$$\text{Heat generated} = \frac{0{\cdot}2388 I^2 Rt}{252} = \frac{0{\cdot}2388 \times 4^2 \times 100 \times 600}{252}$$

$$= \mathbf{909{\cdot}9\ B.Th.U.}$$

Then, wt. of water × rise in temp. × specific heat $= 909{\cdot}9 \times \frac{75}{100}$

$$W \times 150 \times 1 = 682{\cdot}4 \text{ B.Th.U.}$$

$$W = \frac{682{\cdot}4}{150} = \mathbf{4{\cdot}55\ lb.}$$

Example 2. *Find how long it would take an electric fire taking* 8·7 *amperes at* 230 *volts to raise the temperature of* 2000 *cu. ft. of air in a room from* 32° *F. to* 62° *F., if* 50% *of the heat supplied is absorbed by the walls, furniture, etc. Take the specific heat of air as* 0·238 *and the weight of the air as* 80 *lb. per* 1000 *cu. ft.*

$$\text{Heat required} = 160 \times 0{\cdot}238 \times (62 - 32) \times \tfrac{100}{50} = 2284{\cdot}8 \text{ B.Th.U.}$$

$$\text{Heat supplied per sec.} = \frac{0{\cdot}2388 \times I^2 R}{252} = \frac{0{\cdot}2388 \times 8{\cdot}7 \times 230}{252}$$

$$= 1{\cdot}896 \text{ B.Th.U.}$$

since $I^2R = EI$ by Ohm's law.

$$\therefore \text{ time taken} = \frac{2284{\cdot}8}{1{\cdot}896 \times 60} = 19{\cdot}96, \text{ say, } \mathbf{20\ minutes.}$$

EXPT. 38.

OBJECT. *To determine the mechanical equivalent of heat by electrical means and to verify Joule's law for the heating effect of a current.*

APPARATUS. A heating unit consisting of a coil of fine wire, a lagged calorimeter, thermometer, stirrer, ammeter and voltmeter. (Fig. 140). The heating unit (Fig. 140 (*a*)) is a coil of fine wire

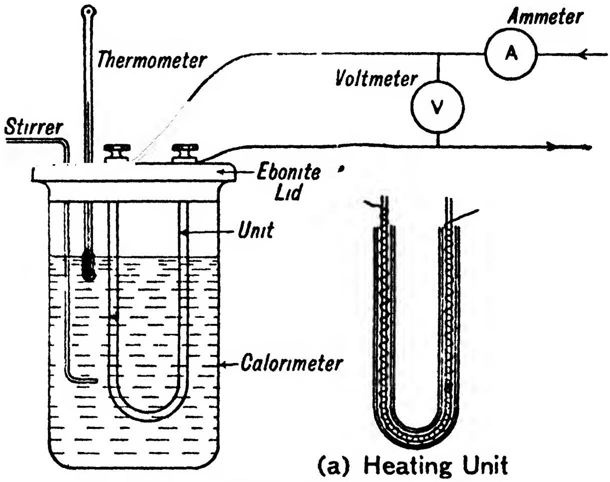


FIG. 140. Apparatus for Joule's equivalent.

wound on to a porcelain frame and then fitted into a metal tube. The terminals on the ebonite lid are then connected to a voltmeter and ammeter in the circuit taken from the bench points in the laboratory.

METHOD OF PROCEDURE. Weigh the empty calorimeter and determine its water equivalent. Three quarter fill the calorimeter with cold water and find the weight of water by weighing the calorimeter and the water. Insert the unit, and note the initial temperature of the water. Allow the current to flow for a carefully timed period, keeping the water gently stirred and the current and voltage readings constant. When the temperature of the water is raised about 20° C., note the final temperature, time of flow, voltmeter and ammeter readings.

OBSERVATIONS.

Weight of calorimeter empty $= 65{\cdot}0$ gm.
Weight of calorimeter + water $= 132{\cdot}5$ gm.

Weight of water	$=67{\cdot}5$ gm.
Water equivalent of calorimeter	$=65\times0{\cdot}095=6{\cdot}175$ gm.
Initial temperature of water	$=18°$ C
Final temperature of water	$=40°$ C.
Rise of temperature	$=22°$ C.
Time of heating	$=25$ sec.
Voltmeter reading	$=110$ volts
Ammeter reading	$=2\frac{1}{2}$ amp.

DERIVED RESULTS. (*a*) Heat given to the water and calorimeter

$$=(67{\cdot}5+6{\cdot}175)\ 22=73{\cdot}675\times22=1620{\cdot}85 \text{ calories.}$$

(*b*) Watts supplied $=110\times2\frac{1}{2}=275$ watts for a period of 25 sec. Since 1 lb. is equivalent to 453·6 gm.

$$(a)=1620{\cdot}85 \text{ calories}=\frac{1620{\cdot}85}{453{\cdot}6} \text{ C.H.U.}=3{\cdot}573 \text{ C.H.U.}$$

Let the mechanical equivalent of heat $=M$.

Then, $\quad 3{\cdot}573 \text{ C.H.U.}=3{\cdot}573M$ ft. lb.

For one second this is $\dfrac{3{\cdot}573M}{25}$ or $0{\cdot}143M$; but in (*b*) 275 watts $=\dfrac{275}{746}$ H.P., and this is $\dfrac{275}{746}\times\dfrac{550}{1}$ ft. lb. per sec., since

$$1 \text{ H.P.}=550 \text{ ft. lb. per sec.,}$$

hence
$$0{\cdot}143M=\frac{275}{746}\times\frac{550}{1},$$

and
$$\mathbf{M=1418 \text{ ft. lb. per C.H.U.}}$$

CONCLUSION. (*a*) The correct result is 1400 ft. lb. per C.H.U. and the loss may be traced to a greater time required to heat the water due to losses in the calorimeter. It should be noticed that if the whole of the electrical energy supplied could be used to heat the water, the time of heating would be lessened, with a consequent fall in the value of M.

VERIFICATION OF JOULE'S LAW. Ohm's Law states that the voltage on a closed circuit is qual to the product of the current and the resistance, thus

$$\text{Resistance}=\frac{\text{volts}}{\text{amp.}}=\frac{110}{2\frac{1}{2}}=44 \text{ ohms.}$$

$$\begin{aligned}\text{Heat generated}&=1620{\cdot}85 \text{ calories}\\&=64{\cdot}83 \text{ calories per sec.}\end{aligned}$$

(1) Repeat the experiment for *double the period of time* and verify that the same amount of heat is given per sec.

(2) Arrange for the coil to be supplied with *half the current* and notice that the heating effect is reduced to ¼, thus the heating effect is *proportional to the square of the current.*

Since voltage and current are connected by Ohm's Law, for a given current the heating effect is proportional to the *voltage* and also, therefore, to the *resistance.*

Short circuits. When a breakdown in the insulation occurs, some of the electricity escapes from its intended path and travels either to the earth or to another portion of the circuit. In other words, the electricity takes the line of least resistance, *i.e.* a short cut or short circuit, back to its starting point. Where a large amount of energy is involved, considerable damage can be done to equipment and even buildings when a breakdown in insulation occurs and a short circuit follows. Even with moderate voltages, burning and electrocution may follow if a person allows his body to act as a conductor to earth or to another part of the circuit and so produce a short circuit. It is important therefore to employ devices to control and interrupt short circuits. Exposed metal parts which may become *live*, or carry electricity if a fault occurs, should always be *earthed*, *i.e.* provided with a good continuous metallic connection to earth.

One type of protective device has already been mentioned, namely, the fuse, in which, when the current exceeds a pre-determined amount a metal wire or strip is melted and so breaks the circuit to be protected. To prevent an electrical arc, which occurs when the air between the broken ends of the circuit, when the fuse wire melts, does not set up sufficient resistance and the electricity jumps the gap, the space around the fuse wire is filled with a fire-extinguishing and non-conducting liquid.

Another protective device used in the case of large powers is the **circuit breaker**, which is really a very large switch that opens automatically whenever the current exceeds the pre-determined amount. By submerging the contact points in oil the electric arc formed when the circuit breaker operates is smothered. On high-voltage systems a complete change of oil is necessary after each operation of the breaker.

EXERCISES ON CHAPTER VI

Units and Ohm's Law.

1. How many kilowatt hours are equivalent to one H.P. hour ?

2. A current of 3 amperes is used in the charging of an accumulator during 15 hours. How many coulombs of electricity have been supplied?

3. 100 lamps, each taking 0·2 amperes, run on a 230 volt circuit. Calculate the cost of running per week of 42 hours at 1d. per B.T.U.

4. A motor of 10 B.H.P. runs on full load for a period of 20 hours. If the efficiency is 80%, find the cost at 1d. per B.T.U.

5. The voltmeter reading across the terminals of a dynamo is 230 volts, and the ammeter indicates that a current of 120 amperes is being supplied. What is the output of the dynamo in kilowatts ?

6. Find the resistance of a wire which passes 1·5 amperes under a voltage of 230.

7. A lamp has a resistance of 400 ohms. Find the current taken at 110 volts.

8. What resistance must be put into a circuit in order that a current of 15 amperes may be passed with a 400 volt supply ?

9. State Ohm's Law. Define the international units of resistance, pressure and current.

Heating effect and power.

10. A coil of 40 ohms resistance is connected across a 230 volt main. Find the power consumed.

11. A coil immersion heater of 7500 watts is used to heat 10 gallons of water. Find the rise of temperature produced in 20 min. use.

12. If a lamp taking 0·25 amperes at 230 volts is immersed in a calorimeter of water, find the rise of temperature produced per min. if the water weighs 500 grams and the calorimeter 44 grams. Specific heat of the material of the calorimeter $= 0 \cdot 1$.

13. A conductor generates the heat equivalent of 250,000 joules in a quarter of an hour when a current of 12·5 amperes flows through it. What is the resistance of the conductor ?

14. Find the cost of preparing a bath of 25 gallons of water at ½d. per unit if the necessary temperature rise is 90° F. Efficiency of heater, 80%.

Electrolysis.

15. Explain briefly the terms *electrolyte*, *electrodes*, *cathode* and *anode*.

16. State Faraday's laws of electrolysis and describe any industrial process with which you are acquainted which makes use of the chemical effect of a current.

17. How is the chemical effect of a current utilised in its measurement?

18. Explain the term *electrolysis*. Describe briefly the method used commercially to deposit a layer of metal upon a body.

19. If in a copper voltameter 4·5 grams of copper are deposited on the cathode by electrolysis in 2 hours, what current is passing through the voltameter? Electro-chemical equivalent of copper = 0·0003294 gram per second = deposition by a current of 1 ampere in 1 second.

Cells.

20. What are the necessary constituents for a simple cell? Explain the action of the cell and draw a simple diagram to show the passage of the electric current generated in the cell.

21. Describe a secondary cell or accumulator. Explain the electrochemical action in discharging such a cell, and then show the process of charging. Why is an alternating current unsuitable for charging accumulators?

22. What is the difference between the e.m.f. of a cell and the potential difference across the terminals (*a*) when on open circuit, (*b*) when connected to an external circuit?

23. To what defects is the simple cell subject, and what methods are adopted to lessen their effect?

24. Describe a Leclanché cell briefly, indicating how polarisation is prevented.

25. State how you would show whether an accumulator is fully charged or not.

Resistance, Ohm's law.

26. Distinguish between conductors and insulators. Name three examples of each. What is the best conductor of electricity?

27. Three resistances of 100, 200 and 140 ohms are connected in series. Find the total resistance and the current passed when the voltage is 230.

28. If the three resistances in No. 27 are connected in parallel, what will be the total resistance and current passed?

29. Two resistances, of respectively 20 and 15 ohms, are connected in parallel. The junctions are then connected in series to a resistance of 10 ohms. Find the total resistance.

30. Two lamps take 0·25 amperes each when connected in parallel across a 230 volt supply. Find their total resistance, and the resistance of each.

31. Three lamps of respectively 400, 500 and 600 ohms resistance are connected in parallel across a 110 volt supply. Find the total current taken, and the total resistance.

Heating effect and specific resistance and safety precautions.

32. Find the resistance of 100 feet of copper wire 0·024 in. in diameter. Specific resistance of copper $=0\cdot000000668$ ohm per inch cube.

33. The specific resistance af Eureka metal is 0·0000194 ohm per inch cube. A coil is to be wound with 500 turns of this wire of 0·064 in. diameter. If the average circumference of the coil is 15·2 in., find its resistance.

34. A unit is to have a resistance of 20 ohms. Find the length of copper wire 0·024 in. in diameter required to wind the unit. ($\rho=0\cdot668$ microhm per in. cube.)

35. Two coils of copper wire, (*a*) of 0·064 in. diameter wire, (*b*) of 0·024 in. diameter wire, are to have the same resistance. Calculate the ratio between their lengths.

36. The resistance of the heating unit in a kettle is 75 ohms. Find the quantity of water which can be boiled in 30 minutes on a 230 volt supply if the efficiency of the heater is 88% and the initial temperature of the water 15° C.

37. How does the resistance of a conductor vary with (*a*) its length, (*b*) its diameter ?

Find the diameter of 100 feet of copper wire which shall have the same resistance as 20 feet of copper wire 0·09 in. diameter.

38. A copper wire 0·064 diameter is wound to 500 turns on a bobbin of mean diameter $2\frac{1}{2}$ in. If this is connected in parallel to a similar bobbin of iron wire of 200 turns and diameter of wire 0·05 in., find the individual and total resistances. (ρ for copper is 0·000000668, iron 0·000003795 ohm per cu. in.)

39. Find the resistance of a heating unit, on 230 volt supply, which will boil water from 60° F. at the rate of 4 gallons per hour. Take the efficiency of the heater as 90%.

40. Find the cost of working at 8 hours per day, 6 days per week for 1 year of 20 metal lamps, each having a resistance of 900 ohms and working on a 230 volt supply at 2d. per unit.

41. (*a*) Why is it necessary to connect the metal framework of electric fires to an earth connection?

(*b*) Why are rubber mats provided as standing mats for men operating switch gear?

42. Explain with a sketch the principle of

(*a*) an electric kettle,

(*b*) an electric soldering iron.

43. (*a*) Why is it possible, under favourable conditions, for a cat to walk along a live rail without electrocution taking place?

(*b*) What precautions would be necessary in order that a man may handle live conductors from an elevated platform?

44. (*a*) Why is it considered undesirable to join the starter of a machine to the conduit by means of a piece of flexible metal tubing without an independent connection between the starter and the conduit?

(*b*) In an electrical installation what would you suggest as the best possible earth and why?

45. (*a*) Why is it that damage is seldom done to an iron ship if it is struck by lightning at sea?

(*b*) Account for the regulation that all bathroom switches and fittings, also those fitted in rooms with stone floors shall have no exposed metal parts.

46. How would you preserve an electrically operated wireless set from an overload of electric current? Which of the three effects of a current is this safety device dependent upon?

CHAPTER VII

MAGNETISM—MAGNETIC EFFECT OF A CURRENT—ELECTROMAGNETISM

The magnetic effect of a current. When a current of electricity passes along a wire it is capable of influencing the surrounding medium magnetically, even if only to a small extent, and the effect is greatest near the wire. A **magnetic field** is said to be set up where magnetic phenomena can be detected by means of the repulsion of a compass needle, or by the definite arrangement of iron filings supported on a horizontal sheet of paper. **Magnets** are usually iron or steel bodies which have the permanent or temporary power of attracting and repelling certain other bodies. The most common are the bar and horseshoe types (Fig. 166). When magnets are dipped into iron filings, the power of attraction seems to be confined usually to two definite regions, the central points of which are called the **poles**, and which are usually situated near the ends of the magnets.

Magnetic fields exist in the vicinity of all magnets, and the earth itself acts as a magnet. Hence any magnetic field is really the resultant field due to the earth and to any other magnets present, although in the vicinity of a strong artificial magnet the effect of the earth's magnetism may not be apparent. The pole of a magnet

which, if free to do so, would point towards the north is called a north-seeking pole and marked N (or coloured red), while the other pole which tends to point towards the south is called the south-seeking pole and marked S (or coloured blue). Like poles, such as two N. poles, repel one another, whereas two unlike poles attract one another. If left to its own devices in the earth's magnetic field the N.-seeking pole of a compass needle will point towards the magnetic N. pole of the earth, and the line joining the N. and S. poles indicates the **magnetic meridian,** as it is called, at that place. If a number of needles are placed near a bar magnet, the needles adjust themselves as shown in Fig. 141. The directions in which the compass needles point are determined by the relative attraction and repulsion between the poles of the compass needles and those of the magnet and the earth.

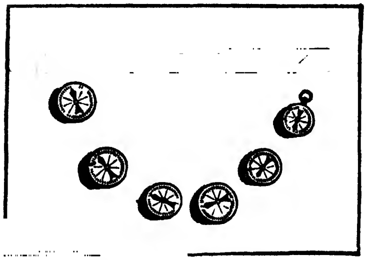


FIG. 141. Directions taken by a compass needle near a magnet.

A magnetic pole is acted upon by a force in a magnetic field, and the line along which the compass needle points is termed the **line of force** passing through that point where the compass needle is placed, and the direction is that pointed out by its N. pole. In the diagram shown, if a fair curve is drawn from the N. to the S. pole of the magnet with the aid of the directions indicated continuously by the compass needles, a line of force is obtained. **All lines of force may be regarded as closed curves,** the loop actually being completed by a line in the magnet itself from the S. to the N. pole. Actually, however, the lines of force exist only outside the magnet, the lines inside the iron are called **lines of induction.** In the same way other lines of force could be obtained for the resultant magnetic field of this magnet and the earth.

Generally an indication of the nature of a magnetic field can be more readily determined by the use of iron filings, as shown in Fig. 142, where a horseshoe magnet is placed underneath a sheet of paper sprinkled with iron filings. A slight tapping of the paper will cause the filings to adjust themselves lengthwise to

indicate the direction of the lines of force. Fig. 143 shows the lines of force in a resultant field due to the earth and to a single north-seeking pole. The point marked with a cross where the resultant

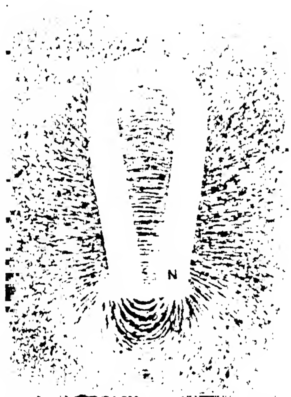


FIG. 142. Map of a magnetic field in a plane of a horsehoe magnet.

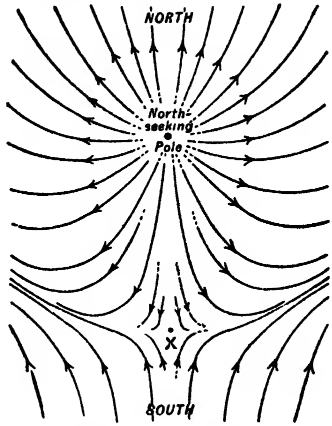


FIG. 143. Resultant field due to the earth and a single north-seeking pole.

field is zero, that is, where the force on unit pole would be zero, is called **a neutral point.** Fig. 144 shows the magnetic field when a bar magnet is placed vertically, and a sheet of paper sprinkled with iron

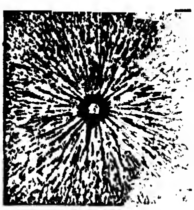


FIG. 144. Map of a magnetic field perpendicular to the axis and near the pole of a bar magnet.

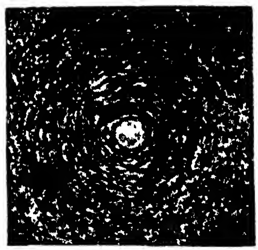


FIG. 145. Map of the magnetic field perpendicular to a wire conveying current.

filings is placed in the plane of one end of the magnet. The lines of force are radial, and the result should be compared with the magnetic field created by a current passing along a straight conductor, as shown in Fig. 145, where the lines of force are concentric

about the axis or centre of the wire. It can be shown by experiment that *the positive direction of the lines of force appears to be clockwise to an observer looking along a wire, which is conveying a current away from him.*

Pole strength and intensity or strength of a magnetic field. A pole has unit strength if it exerts a force of 1 **dyne** on an exactly similar pole placed 1 cm. away in air. The dyne is the absolute unit of force in the centimetre-gram-second or C.G.S. system of units; 1 gram wt. = 981 dynes and 1 lb. wt. = 445,000 dynes in London.

Should the pole strength of two poles be m and m_1 and their distance apart d cm., then the force of attraction, if unlike poles, and of repulsion if like poles, is equal to $\frac{mm_1}{d^2}$ dynes, in accordance with the law of inverse squares (p. 317). Any other combination of forces due to the interaction of attractive and repulsive forces between the poles of magnets may be treated according to the laws of mechanics. *The force in dynes acting on a unit pole, when placed at a point is a measure of the* **intensity or strength of the magnetic field at that point.** Unit magnetic field is that in which a unit pole is acted on by a force of 1 dyne. This unit is called a **gauss**, so that in a field of 3 gauss, a unit pole would be acted on by a force of 3 dynes.

Ampère's rule. This is a rule that is very useful for determining the direction in which a current is flowing when its source cannot be seen. It is usually stated as follows: *Suppose a man to be swimming in the wire with the current and with his face towards a compass needle, then the N.-seeking pole is deflected towards his left hand.*

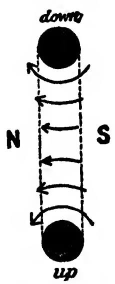


FIG. 146. Magnetic field due to a current in a circular wire.

Fig. 146 shows the nature of the magnetic field set up by a current in a circular wire, the positive direction of the lines of force being clockwise when looking in the direction of current flow. The coil behaves as a magnet, exhibiting N. and S. polarity as can be demonstrated by using a compass needle. The magnetic force due to the current depends upon the strength of the current, and this fact is used in choosing the unit of measurement. *Unit quantity*

of electricity or unit current is that which when flowing along a wire 1 *cm. long bent into the form of a circular arc of* 1 *cm. radius would exert a force of* 1 *dyne on a unit magnetic pole placed at the centre of the circle.* This unit is the absolute unit of current, and is equivalent to a current of 10 amperes. Another definition of the absolute unit of current is given on p. 327, where the subject of magnetism and electro-magnetism is dealt with in a more quantitative way.

The solenoid. In the case of a spiral of wire called a solenoid, as shown in Fig. 147, the lines of force still form closed loops around

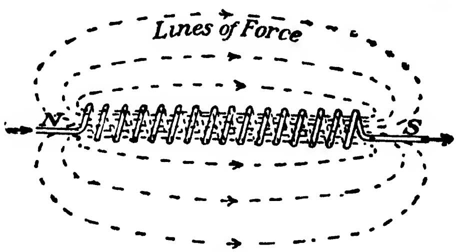


FIG. 147. Magnetic field due to a solenoid in which a current is flowing.

any one turn ; but the shape of the spiral, and its effects, is to produce lines of force, all of which pass through the coil.

The air inside the coil is not easily magnetised, but if an **iron core** is placed inside the spiral, the iron core becomes magnetised with N. and S. poles in the position shown and the magnetic effect is considerably increased, the coil and core behaving exactly like a magnet. If a soft iron core is used, it only acts as a magnet while the current is flowing; the magnetisation is said to be temporary and the iron acts as an electromagnet. When a steel core is substituted, the steel is magnetised to a less extent, but in a more permanent fashion. This property of the solenoid provides the underlying principle in the production of permanent magnets and electromagnets (see Expts. 42, 46 and p. 323).

Comparatively weak permanent magnets can be made by mechanical means (Expt. 41), such as by stroking a bar of steel over its full length, in one direction only, with one pole of a permanent magnet. At this stage it may also be noted that it is possible to magnetise a bar of iron having one pole in the centre and like poles at the ends.

The central pole is then called a **consequent pole**. If broken at a consequent pole the broken ends form like poles of the two magnets so formed. When an ordinary magnet is broken the broken ends exhibit opposite polarity in such a way that the broken pieces act as separate magnets.

Even with so-called permanent magnets the magnetisation can be impaired or destroyed by striking, or heating to a high temperature (refer to Expt. 44). The theory of magnetisation can be strikingly illustrated by magnetising a glass tube filled with iron filings, which become arranged in definite lines with all the N. poles pointing in one direction. When shaken up and disarranged, the glass tube of filings ceases to act as a magnet.

The soft iron core when introduced is really magnetised by a process called **induction**. Magnets possess the property of inducing magnetism in neighbouring pieces of iron and steel. This property is illustrated in Fig. 148, where pieces of iron or steel are first magnetised by induction before being attracted, the polarity of each temporary magnet so formed being such that unlike poles are in contact. To prove this a compass needle may be brought near to the lower end, which is an N. pole and which will repel the N. pole of the compass needle and attract the S. pole. It should be emphasized that this induced magnetism is only of a temporary nature, and the magnetic effect disappears as soon as the magnet is withdrawn or the current is stopped in the solenoid.

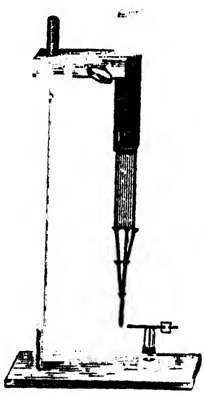


FIG. 148. Magnetic induction and testing for polarity.

The experiments which follow illustrate the matter dealt with in this chapter.

EXPT. 39. **Tangent Law.**

OBJECT. *To verify the tangent law.*

APPARATUS. As shown in Fig. 149.

METHOD OF PROCEDURE. From P, a nail driven into a vertical board, suspend a hanger with weights, of total weight W lb. Attach a small pulley to the board at A and over this pulley pass a light cord terminating in a small ring at B, the ring free to slide up and down

the vertical cord from P. Place a hanger C with adjustable weights on the free end of the cord passing over P.

Now this arrangement represents a simple magnetic or electromagnetic instrument in which the force W is the **restoring force** and the force at C, denoted by W_1 is the **deflecting force**, while the line PB represents the needle. By adding weights to C, or increasing W_1, the line PB is deflected to a position PD. Measure the tangent of the angle BPD, or the angle of deflection, that is, the ratio $\frac{BD}{PB}$ and compare this relation with the ratio $\frac{\text{deflecting force}}{\text{restoring force}}$ or $\frac{W_1}{W}$. Repeat the experiment for various values of W_1 until W_1 almost equals W. It will be found that the ratio of $\frac{\text{deflecting force}}{\text{restoring force}}$ equals the tangent of the angle of deflection, that is,

Deflecting force = Restoring force × Tangent of angle of deflection.

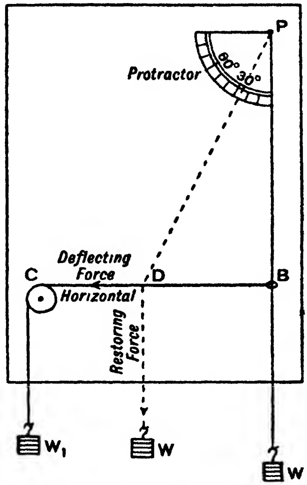


FIG. 149. Expt. 39.

NOTE.—*The student will recognise in this experiment an application of the triangle of forces.*

OBSERVATIONS AND DERIVED RESULTS.

Angle of deflection		W	W_1	$\frac{W_1}{W}$	BD	PB	$\frac{BD}{PB}$
14°	Tan 14° = 0·249	2 lb.	0·5 lb.	0·25	1·9 in.	7·4 in.	0·257
22°	Tan 22° = 0·404	2 lb.	0·8 lb.	0·4	3 in.	7·4 in.	0·405
29°	Tan 29° = 0·554	2 lb.	1·1 lb.	0·55	4·1 in.	7·4 in.	0·554
40°	Tan 40° = 0·839	2 lb.	1·7 lb.	0·85	6·2 in.	7·4 in.	0·838

CONCLUSIONS. **Within the limits of experimental work the values of the tangent of the angle of deflection, the ratio $\frac{W_1}{W}$ and the ratio $\frac{BD}{PB}$ are equal.**

EXPT. 40. **Natural magnets.**

Certain iron ores have magnetic properties and are given the name *lodestones* (=leading stones) for this reason. Take a piece of lodestone and suspend it by a thread passed around the centre. Dip the suspended lodestone into iron filings, when the iron filings will adhere to the lodestone by magnetic attraction. Upon examination of the piece of ore, Fig. 150, the filings will indicate, by their intensity at certain regions, the existence of poles in this natural magnet.

FIG. 150. Natural magnet.

EXPT. 41. **Artificial magnets.**

Take a steel knitting needle which has not been magnetised and dip the end into iron filings; it will be noticed that there is no adhesion of filings. Now magnetise the needle by stroking it in one direction with the North pole of a magnet, using the method of *Single Touch* shown in Fig. 151 (1). Now dip the needle into iron filings; it will be found that it shows definite evidence of magnetisation and that the iron filings adhere to the needle in the region of its poles. These poles may be roughly positioned by shaking a few filings over the length of the

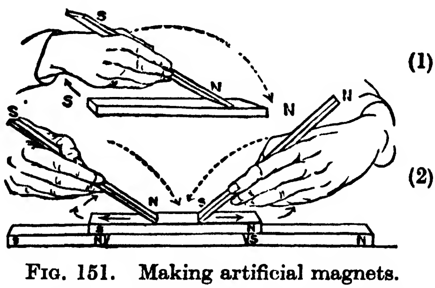


FIG. 151. Making artificial magnets.

needle while it is resting on a card. A slight tapping of the card will then cause these filings to concentrate at the ends of the needle, that is, near the poles. Another unmagnetised needle should now be obtained and magnetised by the method of *divided touch*, Fig. 151 (2), using the N. and S. poles of two magnets and stroking in opposite directions from the centre of the needle towards the ends. Test this artificial magnet by dipping into iron filings.

EXPT. 42. **An electro-magnet.**

Suspend a coil of wire through which is passed an iron rod. Pass a strong electric current for a few seconds through the coil; the suspended coil and rod will set itself in a north-south direction. Remove the rod and test it with iron filings for magnetisation. Replace the iron rod and reverse the direction of the current, when it will be found that the poles of the artificial magnet so formed are also reversed, in other words, the axis of the coil will completely turn around through an angle of 180°.

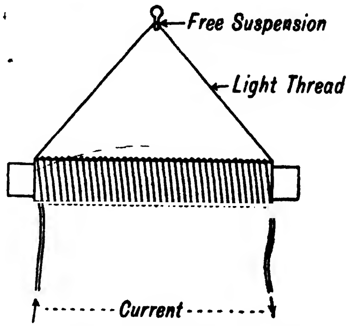


FIG. 152. An electro-magnet.

EXPT. 43. **Test of magnetism.**

APPARATUS. Obtain a strongly magnetised pivoted needle about 4 inches in length with its N. and S. poles clearly marked. Magnetise a knitting needle by one of the methods described in Expt. 41 and take a second knitting needle which is unmagnetised.

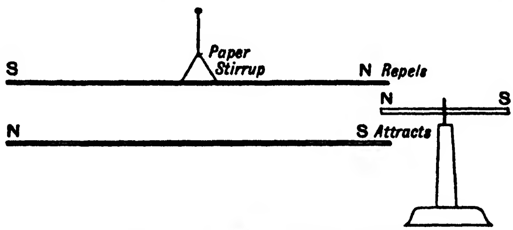


FIG. 153. Test of magnetism.

METHOD OF PROCEDURE. Suspend the magnetised needle in a paper stirrup as shown in Fig. 153, and mark its north-seeking or N. pole by comparison with the pivoted needle, which should be kept at a distance from the suspended knitting needle. Bring the N. pole of the knitting needle into the region of the S. pole of the suspended needle; the two will be found to attract. Now bring the N. pole of the knitting needle into the vicinity of the N. pole of the pivoted needle and notice that the poles repel. Thus, *like poles repel and unlike poles attract.* It now remains to prove that attraction is not a final test of magnetisation of the attracting bodies. Replace the magnetised knitting needle by the unmagnetised one and bring one

end into the vicinity of one of the poles of the pivoted magnet. Attraction will occur. Now bring the other end of the unmagnetised needle near to the pole and again attraction occurs; thus the unmagnetised needle is attracted by either pole of the pivoted magnet, whereas, in the case of the magnetised needle the like poles repelled and only the unlike poles attracted.

Thus, *Repulsion is the only definite test of both needles being magnetised.*

EXPT. 44. **Destruction of magnetism.**

Magnetism may be destroyed by (*a*) rough usage, (*b*) application of heat.

Prepare two magnetised knitting needles and treat them in the following manner.

(1) Place one needle on an anvil and vigorously strike it with a light hammer. Afterwards test for magnetism, when it will be found that all, or nearly all, of the magnetisation will have disappeared.

(2) Heat the other needle to red heat in a bunsen flame, and when it is cool test for magnetism. This treatment will also be found to have destroyed the magnetisation.

EXPT. 45. **Temporary and permanent magnets.**

Take two rods, one of soft iron and the other of steel. Magnetise them separately by means of an electric current and test for magnetism, in each case, by the repulsion of a pivoted compass needle *while the current is still flowing.* Test again for magnetisation after the current is cut off and it will be found that (*a*) the steel remains magnetised, and (*b*) the soft iron has lost most of its magnetisation.

Thus steel becomes a permanent magnet while soft iron is only a magnet while the process of magnetisation is in operation.

EXPT. 46. **To prepare a soft iron cored solenoid.**

The trip gear of starters and contactors is often held in position by a coil of wire known as a solenoid with a soft iron core. Thus while the current is flowing in the coil, the soft iron core behaves as a magnet and attracts the trip gear lever towards its pole. As soon as the current ceases to flow the core becomes demagnetised and the trip gear is released.

METHOD OF PROCEDURE. Wind a number of turns of insulated copper wire loosely around a soft iron core. Fasten the coil and core to a vertical board (Fig. 154) and arrange a soft iron lever

pivoted to a fulcrum on the board, so that the end of the lever can be drawn towards the solenoid core when this is magnetised. Pass a current through the coil; the end of the lever will be drawn by the magnetic force towards the pole of the solenoid core. If the

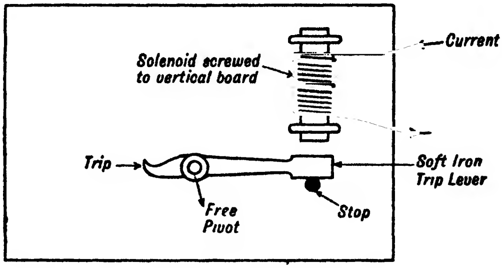


FIG. 154. Trip gear with solenoid.

trip lever is pivoted so that its weight tends to pull it away from the solenoid, and the current circuit is made and broken at intervals, the action of the trip gear can be shown.

EXPT. 47. **Lines of force.**

OBJECT. *To demonstrate the existence of lines of force from a single bar-magnet.*

METHOD OF PROCEDURE. Place a piece of drawing paper on a

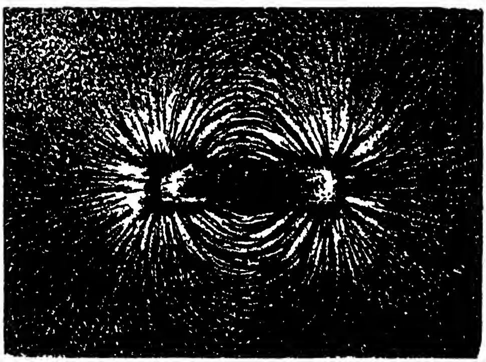


FIG. 155. Magnetic field due to a bar magnet.

drawing board and lay a single bar-magnet upon it (Fig. 155). Sprinkle, in the vicinity of the magnet, some iron filings and gently

tap the board. Each iron filing then becomes a magnet and sets itself along a line of force of the bar-magnet. It will be noticed that the lines of force emanate from the poles of the magnet and that the greatest concentration of lines of force is near these poles.

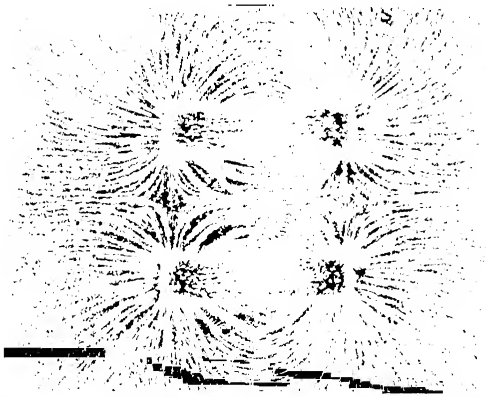


FIG. 156. Magnetic field due to like poles: repulsion.

EXPT. 48.

OBJECT. *To extend experiment No. 47 to two bar-magnets, (a) with poles in opposition, (b) with poles in agreement.*

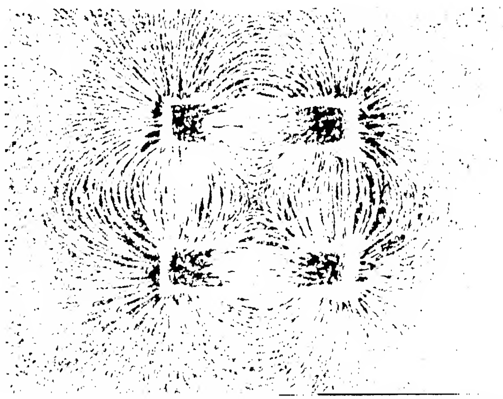


FIG. 157. Magnetic field due to unlike poles: attraction.

Expt. 49. **Lines of force.**

Object. *To map the lines of force of a simple bar-magnet.*

Method of procedure. Place a bar-magnet upon a sheet of drawing paper on a flat table, and obtain a small pocket compass about $\frac{3}{4}$ in. in diameter.

Starting from the end of the magnet, place the compass so that its needle will set itself in the direction of the lines of force of the magnet, as shown in Fig. 141. Mark the two ends of the needle for different positions and join the marks to form continuous and complete lines of force and continue the experiment until a map is obtained of the complete magnetic field.

This experiment may now be extended to two or more bar-magnets placed in the different positions of pole opposition and agreement (see Figs. 141, 143, 156, 157).

Expt. 50. **The magnetometer and the inverse square law.**

Objects. *To demonstrate the validity of the inverse square law and to compare the pole strength of two magnets of equal length.*

Apparatus. A magnetometer and two bar-magnets of equal length (about 24 in.) and of different pole strengths.

The magnetometer (Fig. 158) is an instrument which is made in various forms, the most common of which consists of a compass box

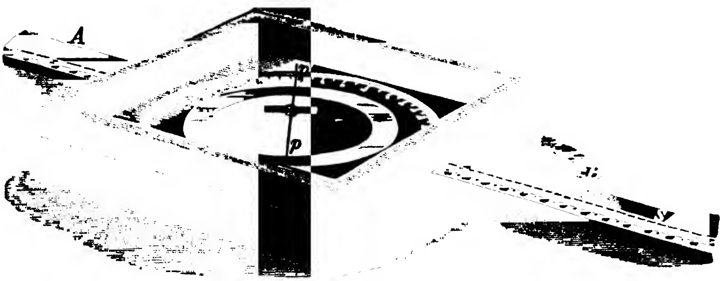


Fig. 158. A magnetometer.

containing a short pivoted magnetic needle to which is fixed, at right angles, a light pointer pp'. This pointer operates over a circular scale graduated in degrees. Through the centre of the box, and in the normal direction of the setting of pp', when the magnet is controlled by the earth only, is a long scale, fitted with a central slot in which a bar-magnet may be placed.

The earth provides a restoring couple on the magnet of the magnetometer while the force due to a pole of the bar-magnet

supplies the deflecting moment (Fig. 159). *If the bar-magnet is comparatively long the influence of the distant pole may be ignored in the proof of the inverse square law and the comparison of pole strengths.*

METHOD OF PROCEDURE. (1) Take one of the bar-magnets, and, after setting the magnetometer so that the light pointer pp' is, without outside magnetic influence, in a line E.-W., that is, the

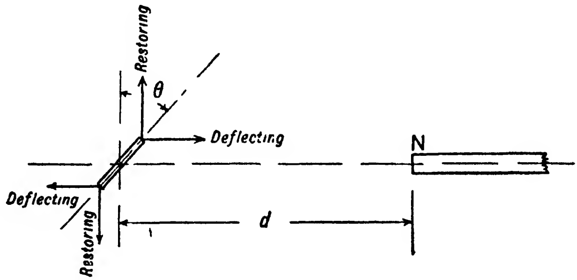


FIG. 159. Forces acting on the pivoted magnet of the magnetometer.

pivoted magnet in a direction N.-S., place the bar-magnet in such a position in the slot that it produces a deflection of about 40° on pp'. Measure carefully the distance d between the pole of the bar-magnet and the centre pivot of the magnetometer needle. Take a series of readings of the magnetometer deflection with varying values of the distance d and tabulate the results. Calculate the values of $d^2 \tan \theta$, where θ is the deflection for the value of d considered.

(2) Place the first bar-magnet in a position to produce a deflection of about 40° and measure the distance d for this magnet.

Replace this magnet by the second bar-magnet in the *same* position and notice the deflection. Now since the distances d are equal for both magnets the pole strengths are proportional to the tangents of the angles of deflection (Tangent Law).

OBSERVATIONS AND DERIVED RESULTS.

(1)

Distance "d" in cm. - -							
Deflection "θ" in degrees - -							
$d^2 \tan \theta$ - -							

Since the force, by the tangent law, is proportional to tan θ, if the force is also, by the inverse square law, inversely proportional to the (distance)^2, $d^2 \tan\theta$ should be a constant.

(2) $\theta_1 =$, $\tan\theta_1 =$, $\theta_2 =$, $\tan\theta_2 =$, **Ratio of pole strengths** $= \dfrac{\text{Tan } \theta_1}{\text{Tan } \theta_2}$.

EXPT. 51. **Magnetic effects of a current.**

OBJECTS. (*a*) *To investigate the magnetic field surrounding a straight conductor carrying a current.*

(*b*) *To verify the rule for the direction of the lines of force surrounding such a conductor.*

APPARATUS. Arrange a straight wire vertically and connect its ends to the terminals of a source of current. Place a stiff card horizontally to surround the conductor (Fig. 160 (*a*)).

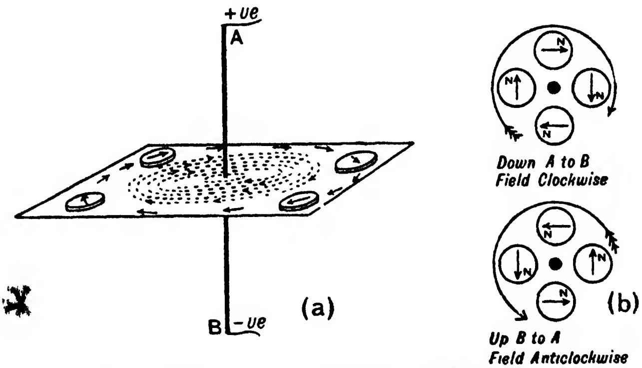


FIG. 160. Magnetic field near a long straight conductor.

METHOD OF PROCEDURE. Pass the current down the conductor from A to B and sprinkle on the card, evenly, some iron filings. Tap the card gently and notice that the filings take up positions in concentric circles around the conductor. Reverse the current direction and notice that the same circular form of the lines of force is maintained. Note the direction of the current flow is from the positive terminal of its source towards the negative. Next remove the filings and employ a small test compass to determine the direction of the lines of force. When the current is flowing from A towards B it will be found that the direction of the lines of force is clockwise in plan, that is, the compass needle will turn itself with the N.-S. line in a clockwise direction. Upon reversing the direction of the

current the direction of the lines of force will become anticlockwise (Fig. 160 (*b*)).

CONCLUSION. (*a*) The lines of force surrounding a straight conductor carrying a current are concentric circles with the conductor passing through their centre.

(*b*) If you look along a conductor in the direction of the current flow, the field around the conductor is such that the north seeking pole of a magnet placed in the plane of the lines of force will set itself to point in a clockwise direction. This is equivalent to **Maxwell's Corkscrew Rule,** which states *that if you imagine a corkscrew being driven along the wire in the direction of the current, a N. pole of magnet placed in the field will set itself in the direction moved by the handle.*

EXPT. 52. **Magnetic field round a circular conductor.**

OBJECTS. (*a*) *To investigate the magnetic field surrounding a circular conductor carrying a current.*

(*b*) *To show that the direction of the lines of force is according to the rule verified in Expt.* 51.

APPARATUS. A circular coil of wire attached by terminals to a base board. A source of current and a stiff card fixed diametrically across the coil at right angles to it (Fig. 161).

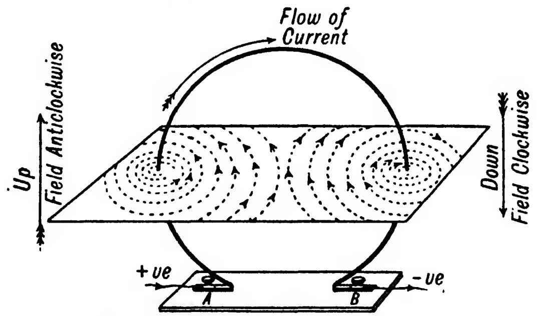


FIG. 161. Magnetic field surrounding a circular conductor.

METHOD OF PROCEDURE. Pass a current around the coil from A to B; that is, connect the terminal A to the positive and B to the negative of the source of current. Sprinkle iron filings on the top of the card and gently tap. The filings will set themselves in the direction of the lines of force, which will be in two series of concentric rings surrounding the two limbs of the coil. Examine this arrangement of lines of force, and it is found to be consistent with

the conclusion of Expt. 51, that is, in the left-hand limb, the current is flowing upwards so that the north-seeking pole of a test magnet will indicate an anticlockwise direction of the lines of force. Similarly in the right-hand limb the current is flowing downwards and a test compass will indicate a clockwise direction of the lines of force. Test for the accuracy of this theory by placing a test compass at different points in the field of each limb. Reverse the direction of the current flow and verify the change of direction of the lines of force.

EXPT. 53. **Magnetic effects of a current.**

OBJECTS. (*a*) *To investigate the field surrounding a solenoid carrying a current.*

(*b*) *To determine the polarity of the ends of this solenoid.*

(*c*) *To show the effects on the magnetic field by the presence of an iron core in the solenoid.*

APPARATUS. Prepare a solenoid by winding fairly closely on to a cardboard hollow cylinder some turns of thick insulated wire (Figs. 162, 163). Cut a sheet of cardboard to fit the outside of this solenoid in a plane containing its longitudinal axis, and connect the ends of the solenoid winding to a source of current. Obtain a pivoted compass needle and a soft iron core for the solenoid.

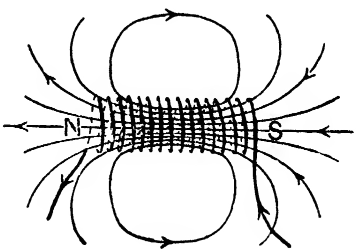


FIG. 162. Solenoid and magnetic field.

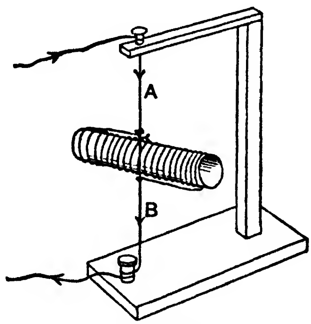


FIG. 163. Expt. 53.

METHOD OF PROCEDURE. Pass a current through the solenoid and note the direction of flow. Sprinkle iron filings on the card and gently tap. Note the distribution of the lines of force. Bring the north pole of the test magnet near each end of the solenoid in turn and verify the polarity of the ends by the repulsion test, Expt. 43.

Clear the iron filings from the card and slowly introduce the iron core into the solenoid while the current is flowing. Notice the

tendency for the core to be drawn into the coil. Now sprinkle the filings on the card and notice the tendency for the whole magnetic field to be concentrated in the iron, and a comparative absence of magnetic effect around the coil itself. Test the polarity of the ends of the iron cored solenoid and notice that they are the same as for the coil alone. Reverse the direction of current flow and again test for polarity. This time the polarity of the ends will be reversed.

CONCLUSIONS. 1. The magnetic field around a solenoid (Fig. 162) is in the form of closed loops which pass and are concentrated through the centre of the coil.

2. When an iron core is introduced into the centre of the solenoid, this coil is drawn into the coil.

3. The lines of force become concentrated in the iron core and there is very little evidence of the existence of an external field.

4. The coil ends assume a polarity according to the direction of the current flow.

Example 1. *A north pole of strength 27 units is placed 5 cm. from a south pole of strength 36 units. Find the force exerted.*

Using the relation $F = \frac{mm_1}{d^2}$ where $m = +27$, $m_1 = -36$ and $d = 5$ cm.,

$$F = \frac{27 \times -36}{5^2} = -38{\cdot}88 \text{ dynes (attraction).}$$

The nature of the force is attraction, since the poles are unlike, and the answer is negative, and the poles are said to exert an attractive force on each other of 38·88 dynes.

Example 2. *Two north poles of strengths 18 and 54 units respectively are placed 9 cm. apart. Find the force exerted between them.*

$$F = \frac{mm_1}{d^2} \text{ where } m = 18,\ m_1 = 54,\ d = 9$$

$$= \frac{18 \times 54}{9^2} = 12 \text{ dynes (repulsion).}$$

Example 3. *A magnet pole has a strength of 300 units. Determine the strength of the magnetic field at a distance of 15 cm.*

Since the strength of the field is the force on a unit pole, the values of m and m_1 are 300 and 1.

$$H = \text{strength of field} = F = \frac{mm_1}{d^2} = \frac{300 \times 1}{15 \times 15} = 1\tfrac{1}{3} \text{ gauss.}$$

NOTE.—The force acting on a pole of strength say 3 units, at this point would be $3 \times 1\frac{1}{3} = 4$ dynes.

Example 4. *Two long magnets are placed in line with their S. poles 10 cm. apart. If the pole strengths are respectively 30 and 50, find the position of the neutral point, that is, the point where the field due to one pole is equal to that due to the other. Since the magnets are long the effects of the N. poles may be neglected.*

Let the neutral point be x cm. from the pole of strength 30, and $(10-x)$ cm. from that of pole strength 50 units.

At the neutral point the field strengths are equal, and

$$\frac{30\times 1}{x^2}=\frac{50\times 1}{(10-x)^2} \text{ or } 3000-600x+30x^2=50x^2,$$

whence $x=4{\cdot}365$ **cm.**

Electromagnets. The property of being able to induce magnetism is of great importance in the production of electromagnets and in all electrical machinery which employs them. Fig. 164 shows the principle underlying the making of a horseshoe electromagnet. The thick core of soft iron has several turns of thick cotton-covered wire wound opposite ways around each straight limb, and the ends connected to a battery or other source of continuous current supply. The current will flow around the left-hand limb first, and then through the coil around the right-hand limb, producing an S. pole at the extremity of the left-hand limb and an N. pole at the other. The polarity can be tested by using a compass needle. By reversing the direction of flow of the current the polarity will also be reversed.

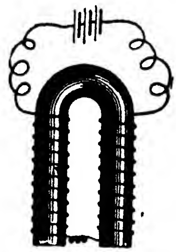


FIG. 164. A simple electromagnet.

Electromagnets are used nowadays for lifting iron and steel parts, and for gripping them in magnetic chucks while machine operations are carried out. When the work is to be released a demagnetising switch causes a reversal of the flow of current, which demagnetises the iron and allows the work to be removed before the magnetism is built up with this reversed polarity. This also serves to demagnetise the work. In modern designs of electromagnets for magnetic chucks, large numbers of turns are coiled around each pole piece, and the coils insulated from each other by employing enamelled

wire, paper separators, and finally forcing an insulating compound into all the interstices between the coils.

Soft iron is chosen for the core of the electromagnet because only a small expenditure of energy is required to magnetise it, and for this reason it is said to have high **permeability**. The latter indicates the degree of ease with which the lines of induction establish themselves in a material. Fig. 165 shows the effect of placing a piece of soft iron in a uniform magnetic field. The lines of induction tend to crowd through the iron, strengthening the field at A and B and weakening it at C and D. This piece of soft iron now acts as a magnet, its actual strength depending upon the strength of the field, with an S. pole at the end A and an N. pole at the end B. Thus magnetisation has been induced without actual metallic contact. Note that when soft iron entirely withdraws lines of force from any region it is said to serve as a magnetic screen. Material which has a high permeability is said to have a low **reluctance**, a term which may be defined as the resistance to the establishment of induced magnetism.

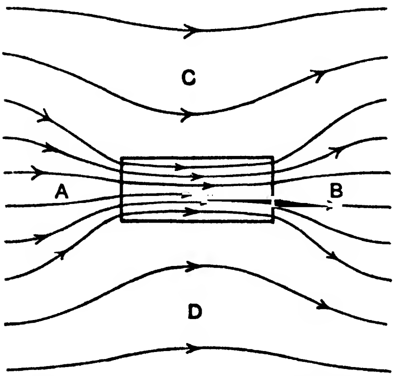


FIG. 165. Resultant lines of induction for a piece of soft iron in a magnetic field.

A soft iron **keeper** or **armature** placed across the poles of a permanent horseshoe magnet (Fig. 166) has magnetism induced into it, and the closing of the magnetic circuit gives the material of the magnet greater power of retaining magnetisation; this power is termed **retentivity**. The efficiency of the magneto, used sometimes for creating an electric spark in an internal combustion engine, depends upon the ability of the magnets to

FIG. 166. Horseshoe magnet with keeper.

retain their magnetism. Hard steel which contains such metals as cobalt and tungsten has a high retentivity.

The magnetic circuit. If unit pole is situated at the centre of a sphere of 1 cm. radius, the strength of the field will be uniform over the whole surface of the sphere and, by definition, has a value of 1 unit, called 1 gauss. This means that 1 line of force will cross each square cm., and since the surface area is 4π sq. cm. the total number of lines of force emanating from unit pole is 4π. This gives another definition of unit pole. If the pole strength is not unity, the total number of lines of force starting from any N. pole and ending at a S. pole is equal to 4π times the pole strength.

As before mentioned, lines of induction tend to crowd into iron or steel, owing to its high permeability, in preference to passing through air. When the lines of induction exist entirely, or almost entirely, in a closed iron ring, the same number of lines cross each section of the ring, no matter how that cross-section may vary in size and shape. In other words, the total number of lines of induction or **magnetic flux**, as it is generally called, remains the same for each section of the magnetic circuit. Magnetic flux is a general term used for both lines of force and lines of induction, which together comprise a magnetic circuit.

Electro-magnetism. Work done in moving a magnetic pole in a uniform field. Since the strength of the magnetic field at any point is the force acting on unit pole if placed at that point, then, conversely, the force F acting on a unit pole placed in a field of uniform strength H will be H dynes. The direction of the force on a magnetic pole placed in a field of strength H is in the same direction as the lines of force if the pole is a N. pole and opposite to the direction of the lines of force if it is a S. pole. H is also called the magnetising force and is measured by the number of lines of force per sq. cm.

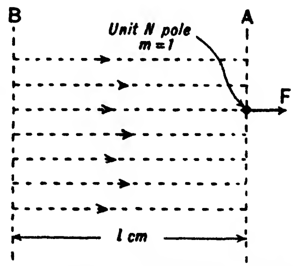


FIG. 167. Uniform magnetic field.

Now consider a unit N. magnetic pole placed in a field of uniform strength H (Fig. 167). This is a reasonable assumption as exempli-

fied by the earth's field at a given place or near the pole of a powerful electro-magnet, or in a closed magnetic circuit. The force F acting on the pole will be H dynes and its sense of direction will be from left to right. Assume an equal and opposite force to be applied to the pole so as to move it in the opposite direction from A to B through a distance l cm. parallel to the lines of force. The energy expended in this movement

$$= \text{Force in dynes} \times \text{displacement in cm.}$$

$$= \quad H \quad \times \quad l \text{ ergs} \quad = Hl \text{ ergs},$$

since 1 erg is the work done when a force of 1 dyne acts through a distance of 1 cm., measured parallel to the direction in which the force acts. The erg is the absolute unit of work in the C.G.S. or centimetre, gram, second system of units.

This energy is not lost but is only stored up, as in the case of a perfectly elastic spring which has been compressed by a force, and may be regained by allowing the pole to move back to the position A under the force F; in a similar way the resilience or work stored by a spring may be regained, by allowing the spring to resume its former shape, while acting against the force which was used to compress it.

This energy is called the **magneto-motive force** (m.m.f.) of the magnetic field between the points A and B, because it plays the same part in the magnetic equation for the magnetic circuit as does the e.m.f. in the electrical equation for the electric circuit (see p. 330).

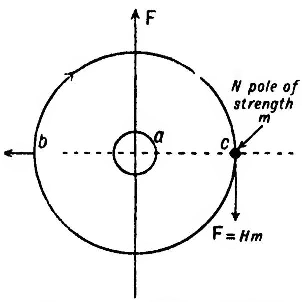


Fig. 168. Force acting on a conductor.

Note.—Where the field is not uniform the treatment of the m.m.f. is much more complicated and is not considered in this book.

Force acting on a conductor. Fig. 168 shows the direction of the lines of force around a conductor a in which the current is flowing away from the observer.

Let the field strength, due to the current in the conductor, a, at the point c, where a magnetic N. pole of strength m dynes is placed, be H.

Then the force experienced by the pole will be $F = Hm$ dynes, and the direction of the force will be as indicated by the arrow, *i.e.* tangential to the circle. An equal and opposite reaction F will be experienced by the conductor.

This reaction may be assumed to be brought about by the current carrying conductor being placed in the magnetic field due to the pole of strength m. In this case, let cb be one of the lines of force emanating from the pole which passes through the centre of the conductor. The force experienced by the conductor will thus be perpendicular both to *this* field and to the length of the conductor as explained below. A reversal of current will reverse this force, as will also a reversal of the magnetic field due to the pole (*i.e.* by changing it to a S. pole).

Now assume a conductor (Fig. 169) to be placed in a magnetic field with its length l cm. perpendicular to the lines of force and with a current of strength I' in absolute units flowing along it. If the field strength is H, experiment shows that the force F is directly proportional to the length l, the field strength H and the current I'.

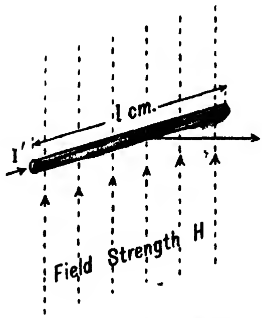


FIG. 169. Force acting on a conductor in a uniform field.

Now, *the absolute unit of current is* defined as *the current which, when passing through a conductor* 1 *cm. in length placed in a magnetic field of one line per sq. cm., so that it is perpendicular to the lines of force, produces a force of* 1 *dyne between the conductor and the magnetic field.*

Thus, the force F acting on the conductor l cm. in length in a field of strength H lines per sq. cm., and with a current of I' absolute units in the conductor, is, from the definition of unit current,

$$F = HI'l.$$

Compare the above definition of absolute unit of current with that on p. 309.

Let an equal and opposite force be applied to the conductor to move it through the magnetic field a distance d, parallel to the line of action of the force.

Then energy expended $= F \times d = HI'ld$

$= H \times I' \times$ Area swept out by conductor

$= \phi I'$, ...(1)

where ϕ = total flux cut across = field strength × area

= total number of lines cut across $= Hld$.

Field due to a current in a long straight conductor. Let a current of I' absolute units flow in a straight conductor and at a point r cm., measured perpendicularly from the conductor, let the field strength be H dynes. Then the force F acting on unit magnetic pole when placed at this point will be H dynes.

Now let the pole be moved once round the conductor axis as centre in a circular path of radius r cm. against the force F.

The distance moved $= 2\pi r$ cm ,

and the energy expended $= F \times 2\pi r$ or $2\pi rH$ ergs ....(2)

= m.m f of the field at the radius r.

However, in moving the pole once round the long conductor every one of the 4π lines of force emanating from the unit magnetic pole cuts across the current carrying conductor.

Since from equation (1) above the energy $= \phi I'$, and $\phi = 4\pi$ in this case, then

$$\phi I' = 4\pi I'.$$

Thus $4\pi I'$ must equal the m.m.f.

and $$2\pi r H = 4\pi I,$$

or $$H = \frac{4\pi I'}{2\pi r} = \frac{2I'}{r}. \qquad \text{..........................(3)}$$

Magneto-motive force for a solenoid. Let the solenoid have T turns and the current flowing be I' absolute units. A current I' flowing through T turns can be considered as equivalent to a current of (TI') units flowing in one turn.

If it be assumed that a unit magnetic pole be moved once through the turn, in a circular path through a point on the axis of the turn, round and back again to its starting point, in a direction opposite to the force acting on it, then every one of the 4π lines of force from the pole cuts across the conductor, and as already explained,

m.m.f. = energy $= \phi \times$ current $= 4\pi TI'$. ....(4)

Field strength inside a closed ring. Consider a spiral of wire made from a large number of evenly wound turns T and bent round to the shape of an anchor ring and carrying a current of I' absolute units. Let the mean radius of the ring be R cm. and the mean length l cm.

Then $$2\pi R = l.$$

Suppose H is the field strength at the centre of the turns or on the mean circumference of the ring.

Then from the consideration of the energy expended by a unit pole in traversing the mean circumference of the ring in the opposite direction to the lines of force,

$$\begin{aligned} \text{m.m.f.} &= 2\pi RH = lH \\ &= 4\pi TI' \text{ from equation (4), p. 328.} \end{aligned}$$

$$\therefore\ H = \frac{4\pi TI'}{l}. \quad \ldots\ldots \qquad \ldots\ldots(5)$$

In the magnetic circuit the

$$\begin{aligned} \text{total flux } \phi &= \text{field strength} \times \text{area of cross-section of ring} \\ &= H \times a \\ &= \frac{4\pi TI'}{l} \times a = \frac{4\pi TI'}{l/a} = \frac{\text{m.m.f.}}{\text{Reluctance}}. \end{aligned}$$

l/a is called the **reluctance** or the resistance set up to magnetisation of the air within the wire coils and it plays the same part in the magnetic circuit as resistance does in the electrical circuit.

NOTE: in the above formulae the current I is expressed in absolute units. If the current be measured in amperes, then I' must be replaced in the above formula by $I/10$.

With an *iron core* the total flux is increased by lines of induction and the flux density or ϕ/a is denoted by the symbol B.

Permeability is measured by the ratio $\dfrac{B}{H}$, and is denoted by the Greek letter μ. $\mu = 1$ for air.

H, it must be remembered, is the magnetising force.

In the case of a closed iron ring which is subjected to a magnetising force by a current passing through a coil wound round it, the magnetising force producing a flux in the iron ring is $H = \dfrac{4\pi TI}{10l}$, where l is the mean length of the ring in cm.

The total flux $=\Phi=B\times$ area

$$=Ba=\mu aH=\frac{4\pi TI}{10l}\times a\mu$$

$$=\frac{4\pi TI}{10}\div\frac{l}{a\mu}=\text{m.m.f.}\div\text{reluctance.}$$

As before, the quantity $\frac{4\pi TI}{10}$ is called the magneto-motive force (m.m.f.), and $\frac{l}{a\mu}$ is called the reluctance (S) or resistance set up to magnetisation.

A comparison may now be made between the laws of the electric and magnetic circuits :

Electric circuit : current = e.m.f. ÷ resistance (variation of Ohm's law).

Magnetic circuit : total flux = m.m.f. ÷ reluctance.

As in the electric circuit, *the relation just given for the magnetic circuit is true for a portion of the circuit as well as for the whole.*

Flux density and magnetising force. In the case of an electro-magnet in which a pole strength m is induced, then $\frac{4\pi m}{a}$ lines of induction will pass through the iron per sq. cm. if a is the area of a uniform cross-section in sq. cm. If H is the magnetising force, that is, if H lines per sq. cm. passed previously, then $H+\frac{4\pi m}{a}$ is the total lines passing per sq. cm. This is called the **flux density** or induction, and is denoted by the symbol B.

Hence $B=H+4\pi\frac{m}{a}=H+4\pi J$, where $J=\frac{m}{a}$ and is called the intensity of magnetisation.

Curves showing the relationship between the magnetising force H and the flux density B for a few common brands of iron and steel, nickel and radiometal are shown in Fig. 170. The steepest parts of the curves indicate where the magnetic induction is increasing very rapidly for a small increase in the magnetising force. This is a very desirable feature, and materials which have a steep B *v.* H curve, initially, should be chosen where possible for the magnetic circuits of

electrical machines. μ *v.* H curves can easily be constructed from B *v.* H curves, since $\mu = \frac{B}{H}$.

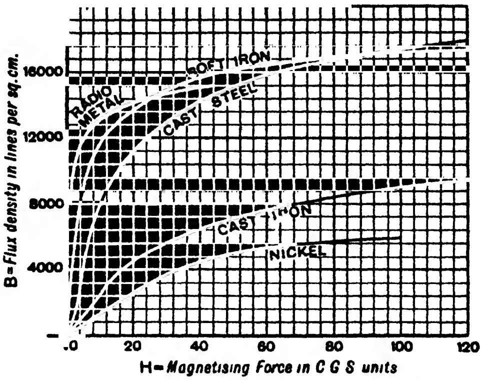


FIG. 170. Flux density *v.* magnetising force.

The strength of the magnetic field H, or the numbers of line of force per sq. cm. at right angles to their direction, at the centre of a solenoid is given by the formula :

$$H = \frac{4\pi TI}{10l}, \text{ where } \begin{cases} T = \text{number of turns,} \\ I = \text{current in amperes,} \\ l = \text{length of solenoid in c....,} \\ TI = \text{the ampere turns of the solenoid.} \end{cases}$$

This formula may be written :

$H = 1{\cdot}257 \times$ *number of ampere turns per cm. length of solenoid.*

Summary of units of measurement.

The practical unit of quantity of electricity is called the **coulomb**, and it is considered to be the quantity which is transferred at any point of a conductor by a current of 1 ampere in 1 second. The international **ampere** is the unvarying current which when passed through a solution of silver nitrate in water deposits silver at the rate of 0·00118 gram per sec. Resistance is measured by the international **ohm**, which is the resistance offered to a constant electric current by a mercury column 106·3 cm. long of unvarying cross-section, weighing 14·4521 grams, and at a temperature of 0° C.,

that is, of melting ice. Pressure is measured as the voltage; the international **volt** is that pressure which, on being steadily applied to a conductor of resistance 1 ohm, will produce a current of 1 ampere. The unit of work is called a **joule**, and is the energy expended by 1 coulomb of electricity in any part of a circuit between the ends of which a pressure of 1 volt exists.

Since $$\text{coulombs} = \text{amperes} \times \text{seconds},$$

the amount of energy expended in a circuit with pressure E volts and current I amperes in t seconds is EIt joules; 1 joule $= 10^7$ ergs $= 0{\cdot}7372$ ft. lb. When the rate of doing work is 1 joule per sec. the power developed is described as 1 **watt**. Thus the product

$$\textbf{amperes} \times \textbf{volts} = \textbf{watts.}$$

This electrical unit of power is often too small for many purposes, so that a larger unit, the **kilowatt** (kW.), or 1000 watts, is employed.

The **Board of Trade unit** (B.T.U.) of electrical energy, or the standard unit of energy, is a supply of 1 kilowatt maintained for 1 hour, that is, a **kilowatt hour** (or Kelvin). Since **746 watts are equivalent to 1 horse power**, a conversion of watts to horse power may be made by dividing the number of watts by 746. A power of 746 watts is often referred to as an electrical horse power.

Example 1. *A solenoid* 40 *cm. long has* 800 *turns and carries a current of* 12 *amperes. Determine* (1) *the m.m.f.*, (2) *the magnetic force at the centre of the solenoid, and* (3) *the total flux if the cross-sectional area is* 3 *sq. cm.*

$$\text{m.m.f.} = \frac{4\pi TI}{10} = 1{\cdot}257 \times 800 \times 12 = \textbf{12,067 units.}$$

$$H = \text{magnetic force} = \frac{4\pi TI}{10l} = \frac{4\pi \times 800 \times 12}{10 \times 40} = \textbf{301·7 dynes.}$$

$$\Phi = \text{total flux} = \mu a H = 1 \times 3 \times 301{\cdot}7 = \textbf{905 lines.}$$

Example 2. *Find the number of ampere turns required per cm. length for a solenoid taking* 10 *amperes if the magnetic field at the centre is to be* 1200 *times as strong as the earth's horizontal field, which is* 0·18 *gauss?*

$$\frac{4\pi TI}{10l}, \text{ in which } H = 1200 \times 0{\cdot}18, \text{ and } \frac{TI}{l} \text{ is required.}$$

$$\frac{TI}{l} = \frac{10H}{4\pi} = \frac{10 \times 1200 \times 0{\cdot}18}{4\pi} = \mathbf{17{\cdot}2}.$$

Example 3. *Calculate the ampere turns and the magneto motive force needed to create a flux density of* 12,000 *lines through a solid circular ring of mean diameter* 20 *cm. and of square section,* 2 *cm.* × 2 *cm. What is the total flux?* $\mu = 1900$.

$$B = \mu H = \frac{4\pi TI}{10l}\mu, \text{ in which } \begin{cases} B = 12{,}000, \\ l = 20\pi \text{ cm.}, \\ \mu = 1900. \end{cases}$$

Then $$TI = \frac{10Bl}{4\pi\mu} = \frac{10 \times 12{,}000 \times 20\pi}{4 \times \pi \times 1900} = \textbf{316 ampere turns.}$$

$$\text{m.m.f.} = \frac{4\pi TI}{10} = 1{\cdot}257 \times 316 = \textbf{397·2 units.}$$

Example 4. *If an air gap of* 2 *mm. is cut in the above ring, find the ampere turns and m.m.f. necessary to send a flux density of* 12,000 *lines across the gap.*

As above, $$TI = \frac{10Bl}{4\pi\mu} = \frac{10 \times 12{,}000 \times 0{\cdot}2}{4\pi \times 1} \quad \begin{cases} B = 12{,}000, \\ l = 0{\cdot}2 \text{ cm.} \\ \mu = 1. \end{cases}$$
$$= \textbf{1910 ampere turns.}$$

$$\text{m.m.f.} = \frac{4\pi TI}{10} = \textbf{2400 units.}$$

A comparison of the ampere turns required for the two cases worked in Examples 3 and 4 shows why the air gap in the magnetic circuit for electrical machines is always reduced to a minimum.

EXERCISES ON CHAPTER VII

Magnetism.

1. What is meant by the *poles of a magnet*? How would you locate the poles of a bar magnet, and where would you expect them to be situated?

2. How is the pole strength of a magnet measured? Explain the reduction in magnetic influence upon a body as it is moved away from the pole. What law governs this influence?

3. What are the tests for magnetism? If two pieces of steel are brought near each other, and one is pulled towards the other, are both pieces of steel magnets?

4. Why is repulsion the only test for magnetism? State the laws of attraction and repulsion, and calculate the force of repulsion between two like magnet poles of strength 3 and 5 units situated 4 cm. apart.

5. Prepare a carefully drawn diagram to show the lines of force (*a*) around the poles of a bar magnet, (*b*) in a plane at right angles to a conductor carrying a current, (*c*) in a plane at right angles to a coil and passing through a diameter, when the coil is carrying a current.

6. Draw a diagram to show the nature of the magnetic field of a horseshoe magnet when placed flat on a horizontal table and with its axis of symmetry in the magnetic meridian.

7. Define unit magnetic pole. What happens when a magnet is broken in half (*a*) if it has no consequent poles, (*b*) if it has a consequent pole ?

8. Devise two experiments to support the generally recognised theory of magnetisation.

9. What is the meaning of the words *magnetic induction* ? Describe a simple experiment to explain the phenomenon, including a test for the polarity induced. Can magnetisation be induced in soft iron when an air gap separates a permanent magnet from the iron ?

10. Calculate the forces acting between two magnetic poles of strengths 40 and 70 placed 10 cm. apart (*a*) if the poles are like, (*b*) if unlike. If the poles are like, find the position of the neutral point.

Electromagnetism.

11. A solenoid is 100 cm. in length and the strength of field inside it is 20·4 units, when a current of 2·5 amperes is passing. Find the number of turns.

12. Find the magneto-motive force for a solenoid of 750 turns passing a current of 3 amperes.

13. A closed iron ring is 40 cm. in mean diameter, and its cross-sectional diameter is 2 cm. Find the reluctance if the permeability is 600.

14. A closed iron ring, 100 cm. in mean length and cross-sectional area 14 sq. cm., is wound with 750 turns, and passes a current of 3 amperes. Find (*a*) the reluctance, (*b*) the flux, (*c*) the magnetic induction or flux density in the ring. $\mu = 600$.

15. A coil of wire is to have an m.m.f. of 4300. If the voltage is 230 and the coil takes $\frac{1}{4}$ kW., find (*a*) the amperes, (*b*) the number of turns, (*c*) the resistance.

16. Find the m.m.f. of a coil of wire of 2000 turns, voltage 230, if the wire is 0·064 in. in diameter, the specific resistance is 0·0000194 ohm per inch cube, and the mean diameter of the coil is 4·4 in.

17. A coil of thick wire carries a current. What will be the effect of passing an iron rod through the centre of the coil. If the coil and rod are now suspended in such a way as to be free to oscillate about its centre point in a horizontal plane, how will the coil behave ?

18. What is the effect of leaving a gap in an iron ring which is wound with wire carrying a current ?

19. What is meant by electro-magnetic induction ? A current flowing in a wire stretched parallel to another wire is constantly being interrupted. If a galvanometer were attached to the parallel wire,

what would you expect to happen? If the current was flowing steadily in the first wire, the galvanometer would behave differently. Why is this?

20. An arrangement is required to break the power circuit in a workshop when the lighting, which is an independent circuit, fails. Sketch and describe a suitable arrangement in which a solenoid is employed.

21. A solenoid is to be used to ensure that the door of an isolating switch box cannot be opened without the current being switched off beforehand. Sketch and describe a suitable arrangement.

22. Sketch an electro-magnet suitable for work in the separation of iron and steel turnings from brass.

23. It is desired to mark the direction N. and S. on the ceiling of a steel-framed building. Why is an ordinary suspended magnetic needle unreliable for this purpose?

24. Why is it most undesirable to take a watch with a steel hairspring into a powerful electric field? What would cause the watch to fail and what is the remedy?

25. How would you test a sample of iron to determine whether or not it was suitable for the core of a solenoid?

26. Calculate the intensity of the field at the centre of a solenoid 55 cm. in length wound on a diameter of 7 cm. with 500 turns and carrying 5 amp.

27. A solenoid is to have a central intensity of field of 25 gauss. Calculate the current if the coil consists of 600 turns on a diameter of 6 cm. and a length of 75 cm.

28. An iron ring of average diameter 20 cm., diameter of metal 2 cm. and wound with 80 turns carries a current of 15 amp. Calculate the total flux. Permeability = 1950.

29. An iron ring of the dimensions given in Example 28 is to have a flux of 25,000 lines. Calculate the necessary ampere turns. Permeability = 2000.

CHAPTER VIII

PRINCIPLES OF GENERATION OF ELECTRICAL ENERGY—GENERATION OF AN E.M.F.—GENERATORS—CONVERSION TO MECHANICAL ENERGY—MOTORS

The generation of an e.m.f. An e.m.f. is created or induced in a conductor whenever there is relative motion between a conductor and a magnetic field. In the diagram (Fig. 171) the magnetic field will be very strong between the two poles of the magnet, and the direction of the field is shown by the arrow F. As the conductor moves in the direction M it will cut across the lines of force and a current will flow in the conductor in the direction I, as can be detected by a sensitive galvanometer, or current measurer, if connected to the ends of the conductor to form a closed circuit. This current only flows while the conductor is moving across the magnetic field, and a reversal of direction of current occurs if the conductor is moved upwards. A useful rule known as **Fleming's Right Hand Rule** for determining the direction of the current in a moving conductor is shown in Fig. 172. *If the* F*orefinger, thu*M*b and se*C*ond finger of the right hand are placed so as to be mutually at right angles, then they indicate respectively and relatively, the direction of the field, of the motion, and of the current.* To create the maximum e.m.f. and current, an intense field must be cut across at right angles as quickly as possible. If any other type of motion takes place, it is only the component at right angles to the field which is useful.

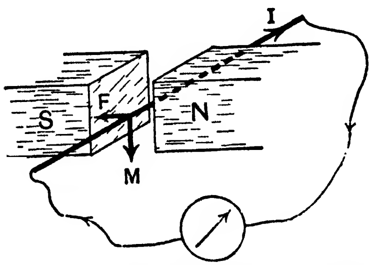


FIG. 171. Conductor cutting across a magnetic field.

Thus, when a conductor is moved through a magnetic field in a direction which has a component velocity perpendicular to the field,

then an e.m.f. is generated or induced in the conductor. The magnitude of this e.m.f. is proportional to the length of conductor l cm. perpendicular to the magnetic field, to the perpendicular velocity v cm. per sec. and to the field strength H lines per sq. cm.

Now the absolute unit of e.m.f. is that generated in a conductor 1 cm. in length when cutting across a magnetic field of unit strength with a velocity of 1 cm. per sec.

Hence e.m.f.,

$$e = Hlv, \tag{1}$$

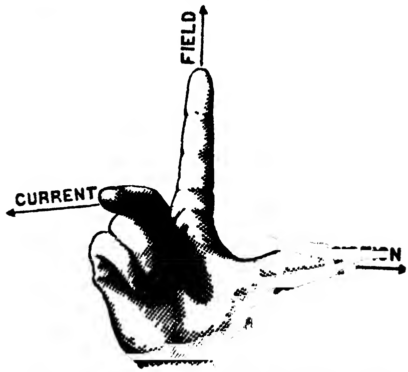


FIG. 172. Fleming's right hand rule.

where e is in absolute units for the conductor just specified.

But the velocity, $v = \frac{d}{t}$, where d is the displacement of the conductor in cm. in t sec.

$$\therefore \; e = \frac{Hld}{t} = \frac{\phi}{t},$$

since the total flux cut is $\phi = Hld$.

Therefore the **generated e.m.f. is equal to the rate of cutting of lines of force per second.**

This absolute unit is very small and the practical unit, the volt, is equal to 10^8 absolute units.

Thus the magnitude of the e.m.f. produced is given algebraically as follows :

$$\text{e.m.f.} = \frac{\text{magnetic flux cut per sec.}}{10^8} \text{ volts.}$$

A current may be induced in a coil by moving a magnet pole towards it, the relative motion causing the lines of force emanating from the magnet to be cut by the coil.

If the conductor is a closed circuit and there is relative motion between this circuit and magnetic field, the currents, which are induced, always tend to set up forces to oppose motion. This is a very important law, and is known as **Lenz's law.**

EXPT. 54. **Induced currents and Lenz's law.**

OBJECTS. (*a*) *To show that an induced current is obtained in a coil only when the number of lines passing through the coil is changed.*

(*b*) *The direction of the induced current is such that the number of lines of force tends to remain constant.*

METHOD OF PROCEDURE. Obtain a circular coil of a large number of turns of thin insulated wire as shown in Fig. 173. Connect the ends of the coil to a galvanometer after previously determining which terminal must be positive so as to give a deflection of the needle to the right. This can be done by using a voltaic cell. Now place the coil on a horizontal table some distance from the galvanometer. The object of the galvanometer is to register that a current is flowing in its coils by deflecting a compass needle at the centre of the instrument.

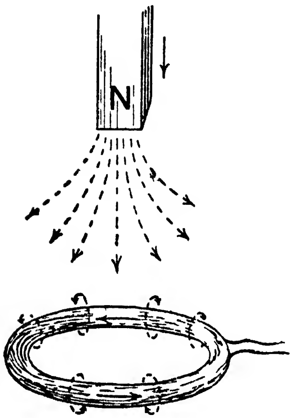


FIG. 173. Expt. 54.

OBSERVATIONS. (*a*) Observe the direction in which the needle is deflected when the N. pole of a bar-magnet is brought towards the coil as shown in Fig. 173. It will be found that the direction of the induced current, due to the number of lines of force passing through the coil changing, is such that the upper end of the coil acts as a N. pole tending to repel the N. pole of the magnet. That is, forces are set up which tend to stop the motion of the magnet, the greater the rate of change of motion the greater the force.

(*b*) Notice the current ceases to flow and the galvanometer needle is no longer deflected as soon as the magnet comes to rest. No relative motion means no induced current.

(*c*) Now withdraw the magnet and notice that the galvanometer needle is deflected in the opposite direction showing that an induced current flows in the coil in the opposite direction, to make the upper side of the coil a S. pole, producing attraction with the withdrawing N. pole. That is, forces are set up which tend to stop the magnet from being withdrawn.

(*d*) Clamp the magnet and move the coil so that the same *relative* motion occurs as in observations (*a*), (*b*) and (*c*). The same results will be noticed.

(*e*) Carry out the observations (*a*), (*b*) and (*c*), but substitute a

S. pole for the N. pole used previously, and note that the directions of the induced currents are reversed. In every case the induced currents set up lines of force which tend to maintain the number passing through the coil as constant as possible; opposing lines tending to neutralise one another when the magnet approaches, and supporting lines tending to strengthen when the magnet is being withdrawn.

(*f*) If a current-carrying coil be substituted for the bar-magnet, similar results will be obtained, according to the direction of the current flowing and the polarity of the faces of the substituted coil.

CONCLUSIONS. The mechanical work done in moving the coil or magnet supplies the energy necessary to generate the induced currents, because no other energy has been given to the system. The observations made are really in conformity with the Principle of conservation of energy and with the idea of inertia in mechanics.

Relationship between mechanical and electrical power. Referring to Fig. 169 and equation (1), p. 337, when the induced current flows in the conductor a force will be set up between the conductor and the magnetic field. From the preceding experiment, or from Lenz's law, this force will tend to oppose the motion of the conductor. If the force assisted the motion of the conductor the velocity of the latter would increase under the action of its own generated currents, and as this would be cumulative, the arrangement would be creating energy, which, of course, is impossible.

Therefore, the e.m.f. generated or induced in the conductor by its motion across the lines of force will be in the opposite direction to the flow of current which would be necessary to produce or assist the same direction of motion in the conductor.

The generated e.m.f., $$e = Hlv, \quad \text{.........(2)}$$

and (from the equation on p. 327, where I' is the current flow in absolute units), the opposing force

$$F = HI'l. \quad \text{.........(3)}$$

Rearranging (2), $$v = \frac{e}{Hl}.$$

Also

$$F \times v = \frac{\text{force} \times \text{displacement}}{\text{time}} = \frac{\text{energy}}{\text{time}} = \text{power} = \text{ergs per second}.$$

$$\therefore \text{ Power} = F \times v = HI'l \times \frac{e}{Hl} = eI' \text{ ergs per sec.}$$

or current × e.m.f. = power.

Now the absolute unit of current = 10 amp. (I),

and ,, ,, ,, e.m.f. $= 10^{-8}$ volts (E).

Substituting in the above, **power** $= 10^8 EI 10^{-1} = 10^7$**EI ergs per sec.**

∴ if the unit of power is chosen so that it is equal to the power in a circuit carrying 1 amp. under a pressure of 1 volt, then this unit will be equivalent to 10^7 ergs. per sec.

Thus **1 watt = 10^7 ergs per sec. = 1 joule per sec.**

Generators. It is upon this generation of e.m.f. and current that the principle of the modern dynamo depends. A large number of conductors are used, and the current generated is collected at suitable points by what is called a **commutator.** A simple form showing the principle as applied to one conductor is shown in Fig. 174. The ends of the rotating coil are joined to the two halves

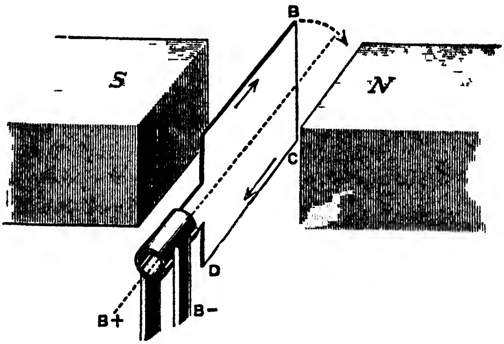


FIG. 174. The principle of a direct current dynamo.

of a split tube which rotates with the coil. As the current which is induced in the branches AB and CD is reversed once during each revolution, the outward flowing current will always pass to the brush B + and return through B −. By increasing the number of coils and corresponding segments of the commutator the e.m.f. and current will not fluctuate so much, and conditions will approximate more nearly to that of the dynamo.

To create an intense magnetic field electromagnets are employed in dynamos; 2, 4, 6 or 8 poles may be used, each N. pole being placed between two S. poles, and the lines of induction crossing from each N. pole through the iron **armature** to the S. poles at each side of it. An iron armature is employed to support the coils and is rotated between the pole pieces. The air gaps separating the armature from the pole pieces are made as small as possible owing to the low permeability of air and this is facilitated by fitting the insulated coils into slots cut in the armature. The magnetic circuit is completed by the lines returning to the N. pole through the iron yoke or outer frame carrying the pole pieces. The coils used to

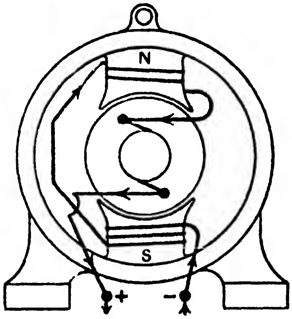


Fig. 175. The principle of a 2-pole series wound dynamo.

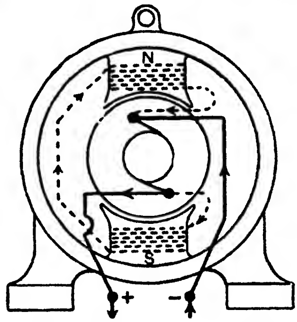


Fig. 176. The principle of a 2-pole shunt wound dynamo.

magnetise the electromagnets are called **field coils**, and the dynamo is said to be separately excited if the current employed is derived from outside sources, and self-excited if the current is taken from the dynamo itself. One method is to arrange for the same current to flow through the armature, field coils and external circuit, in which case the dynamo is said to be **series wound**. A diagrammatic sketch is shown in Fig. 175 for a 2-pole dynamo, the number of turns being few and of stout wire or strip.

Another method is to arrange that the armature current when it leaves the positive brush divides and part passes through the field coils and part through the external circuit. This machine is said to be **shunt wound**, and a diagrammatic arrangement for a 2-pole machine is shown in Fig. 176. A large number of turns of fine wire are used to magnetise the electromagnets. It will be noticed that

part of the current is shunted through the field coils, and the field coils and external circuit are said to be in **parallel.**

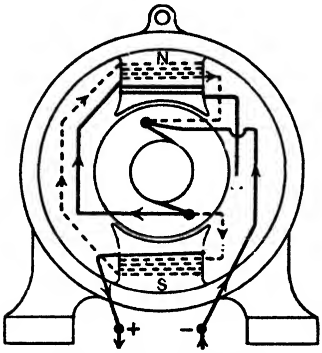


Fig. 177 Compound dynamo (short-shunt type).

In Fig. 177 is shown diagrammatically a 2-pole compound dynamo in which the field coils are partly series and partly shunt wound. This gives to the machine some of the advantages which each type separately possesses, and the machine is said to be **compound wound.**

It has already been shown that

$$\text{Power} = \text{volts} \times \text{amperes}.$$

In a generator, the purpose of which is to maintain a steady e.m.f. in a circuit, the above power is obtained at the expense of mechanical power which is supplied by a prime mover.

Electrical efficiency. This is the ratio of the energy output at the generator terminals to the total electrical energy supplied.

Let the resistance of the armature circuit between generator terminals be R, the total e.m.f. generated be E volts, the current be I amp., the p.d. at the generator terminals be V volts.

Then, from Ohm's law, the voltage equation for the generator is $V = E - IR$ (see Fig. 178), where $R = R_a + R_s$.

Multiplying by I, $$VI = EI - I^2R.$$

Here, VI is the power available for use in the external circuit, EI is the total electrical power converted, and I^2R_a is the heating or copper loss in the armature resistance.

Now, $$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{VI}{EI} = \frac{V}{E}, \quad \text{.....................(1)}$$

or $$= \frac{VI}{VI + I^2R} = \frac{V}{V + IR} \quad \text{.................... (2)}$$

$$= \frac{E - IR}{E}. \quad \text{..................................(3)}$$

From (2) and (3) it is clear that the smaller the armature circuit resistance the greater the electrical efficiency.

Separate and self-excited generators. As before mentioned, in separately excited generators the magnetising current for the field windings is supplied from some external source. This may be a small exciting generator driven from the shaft of the main generator. In self excited generators, to which class the majority of direct current machines belong, the exciting current for the field is supplied by the generator itself, in the following way. A small permanent magnetisation exists in the magnetic circuit of the machine. When the armature revolves e.m.f.'s are generated, and when these are applied to the field winding they produce a small magnetising current which further increases the lines of force. This, in turn, results in an increase in the magnetising current with a further increase in the flux or lines of force. This building up action continues until the e.m.f. generated is just sufficient to maintain a magnetising current capable of producing the necessary magnetic field. In this way the electrical and magnetic circuits become stable.

Self-excited generators, series field windings. In this type the magnetising current is the same as the load current because the field windings are connected in series (Fig. 178), with the armature and external circuit. The *voltage characteristics* are important because they show the way in which the load terminal voltage V varies with the load current.

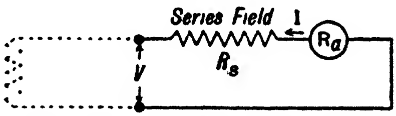


FIG. 178. Connections for a series wound generator.

It has been shown (p. 337) that the e.m.f. generated in a conductor cutting through a magnetic field is Hlv or $\phi \times 10^{-8}/t$ volts per conductor.

The armature winding of a generator consists of a number of conductors connected in such a way that the e.m.f.'s generated in each conductor or arrangement of conductors are additive.

In the above expression,

ϕ, the total flux, is proportional to the flux per pole,

$1/t$ is proportional to $1/$(time for 1 rev.) which in turn is proportional to N, the speed of the armature in rev. per min.

$\therefore$ the generated e.m.f., E, for *any* generator can thus be written, $E = K\phi N$, where K is a constant.

The series field winding for a generator is not used alone to-day, but it is necessary to consider the voltage characteristics for this type of winding when the flux ϕ is proportional to the exciting current as this occurs for smaller values of I, or, in symbols, $\phi = K'I$, where K' is a constant. Now in a series generator I is the load current as well as the field current, so that ϕ increases with the load current.

Thus $E = K(K'I)N$ or CI if $C =$ the constants $KK'N$.

The terminal voltage $V = E - I(R_a + R_s)$, where R_s is the field resistance.

$\therefore$ $V = I(C - R_a - R_s)$, so that V is proportional to I, since C, R_a and R_s are all constant for a given generator and set of conditions.

If the graph V *v.* I is plotted a straight line graph through the origin will be obtained (see Fig. 182).

The shunt generator. In this type the field windings, Fig. 179, are connected in parallel with or shunted across the armature winding.

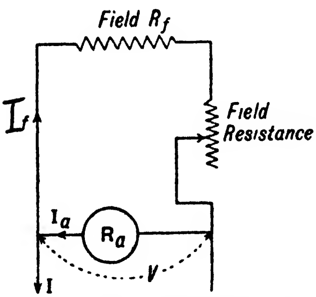


FIG. 179. Connections for a shunt generator.

The field winding consists of a large number of turns, so that the field current necessary to produce the required ampere turns need only be a very small percentage of the load current.

Now $\quad V = E - I_aR_a = K\phi N - I_aR_a;$

so that, *if* ϕ and N are constant, the decrease in the terminal voltage V is equal to the resistance drop or voltage drop due to the resistance of the armature circuit. In modern machines the armature resistance drop is small in comparison with E. Therefore under the above conditions the terminal voltage will only fall by a small amount proportional to the armature current I_a. The latter $= I + I_f$ (Fig. 179), but since I_f, the field current, is small, I may be taken as being equal to I_a.

However, the decrease in V (Fig. 180) will exceed I_aR_a because a decrease in V reduces the field current I_f and consequently the

flux ϕ, but in any case the decrease can only be small. In practice, the decrease in V, due to I_aR_a and to ϕ, may be compensated for, by adjusting the field resistance so as to increase the field

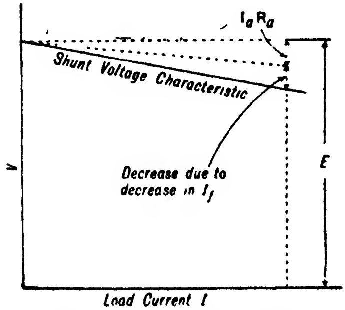


FIG. 180. Shunt voltage characteristic.

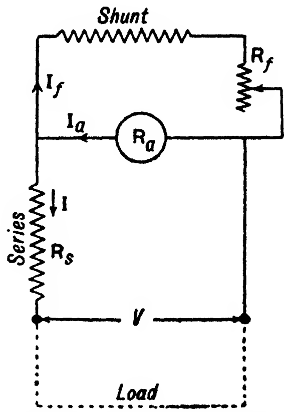


FIG. 181. Connections for a compound generator.

current, and thus ϕ, to make up for the voltage drop or decrease of V.

Compound generator. In this type of generator a small series field (Fig. 181) is used in addition to the shunt field. This series winding increases the flux on load, when the current I increases, to balance the drop due to armature resistance. In this type of generator a suitable value for the series excitation will maintain the terminal voltage constant at all loads. This is known as a level compound generator, Fig. 182. When generators of this type are supplying power through long transmission lines, they are sometimes over-compounded to compensate for the voltage drop in the line. The voltage characteristic is then a rising one.

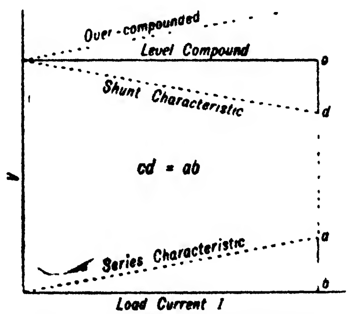


FIG. 182. Characteristics of generators.

Electrical efficiency for the three types of generator.

$$\text{Efficiency} = \frac{VI}{VI + I^2R} \text{ or } \frac{V}{V + IR}.$$

Series. $$\text{Efficiency} = \frac{V}{V + IR} = \frac{V}{V + I(R_a + R_s)},$$

since the resistance R is measured across the generator terminals and $R = R_a + R_s$.

Shunt. If R_f is the resistance of the field winding and regulator, or field resistance, the electrical loss in the field $= VI_f = V^2/R_f$.

$$\text{Armature current} = I_a = I + I_f.$$

$$\therefore \text{ Efficiency} = \frac{VI}{V(I + I_f) + (I + I_f)^2 R_a}$$

$$= \frac{VI}{I_a(V + I_a R_a)}.$$

Compound. $$\text{Efficiency} = \frac{VI}{VI + VI_f + I_a^2 R_a + I^2 R_s}$$

$$= \frac{VI}{I_a(V + I_a R_a) + I^2 R_s};$$

or, since R_s is small and $I_a = I$ very nearly,

$$\text{Efficiency} = \frac{VI}{I_a(V + I_a R_s + I_a R_a)} \text{ approximately.}$$

Example 1. *In a series-wound dynamo the p.d. at the terminals is* 120 *volts. The resistance of the armature and field coils is* 0·4 *and* 0·6 *ohm respectively. Find the e.m.f. and total resistance of the dynamo and watts loss in the dynamo. Hence determine its electrical efficiency. External resistance* = 12 *ohms.*

Total internal resistance $= R = 0{\cdot}4 + 0{\cdot}6 = 1$ **ohm.**

Current in external resistance $= \frac{120}{12} = 10$ amp.

e.m.f. of dynamo = p.d. + $IR = 120 + 10 \times 1 =$ **130 volts.**

Watts loss in dynamo $= EI = I^2R = 10^2 \times 1 =$ **100.**

,, ,, external circuit $= 120 \times 10 = 1200$.

Total watts generated $= 1300$.

$$\text{Electrical efficiency} = \frac{\text{watts in external circuit}}{\text{watts generated}} = \frac{1200}{1300}$$

$= \mathbf{92{\cdot}3\%}$.

NOTE.—This does not include frictional losses of bearings or magnetic losses in the armature iron.

The efficiency can also be obtained by the use of the formula,

$$\text{Efficiency} = \frac{V}{V + I(R_a + R_s)}$$

$$= \frac{120}{120 + 10(0{\cdot}4 + 0{\cdot}6)}$$

$$= 92{\cdot}3\%.$$

Example 2. *In a shunt-wound dynamo the p.d. between the terminals is* 200 *volts, the external current* 120 *amp., and the resistances of the armature and field coils are respectively* 0·05 *and* 40 *ohms. Calculate the current flowing in the field and armature circuits, the watts loss in the dynamo and its electrical efficiency.*

Current in field circuit $= \frac{E}{R} = \frac{200}{40} = 5$ amp.

$\therefore$ Armature current $= 120 + 5 = 125$ amp.

Watts loss in armature coils $= EI = I^2R = 125^2 \times 0{\cdot}05 = 781{\cdot}1$.

" " field coils $= EI = \frac{E^2}{R} = \frac{200^2}{40} = 1000$.

Watts in external circuit $= EI = 120 \times 200 = 24{,}000$.

Total watts generated $= 25{,}781$.

Electrical efficiency $= \frac{24{,}000}{25{,}781} = 93{\cdot}2\%$.

Watts loss in dynamo $= 1781$.

Alternatively, by formula, Efficiency $= \frac{VI}{V(I + I_f) + (I + I_f)^2 R_a}$

$$= \frac{200 \times 120}{200(125) + (125)^2 \times 0{\cdot}05}$$

$$= 0{\cdot}932 \text{ or } 93{\cdot}2\%.$$

Example 3. *A small storage battery, which has an average e.m.f. of* 6·5 volts *and a resistance of* 0·02 *ohms whilst charging, is connected in series with a suitable resistance across* 110 *volt mains. The battery is charged at an average rate of* 4 *amp. for* 15 *hours. Determine* (*a*) *the value of the series resistance,* (*b*) *the cost of charging the battery at* 4*d. per kWh.,* (*c*) *the percentage of the energy taken from the mains which is wasted in series resistance.*

Average e.m.f. producing current in circuit $= 110 - 6{\cdot}5 = 103{\cdot}5$ volts.

Let x be magnitude of variable resistance in ohms, then

total resistance of circuit $= x + 0{\cdot}02$.

From Ohm's law, $I = \frac{E}{R}$ or $4 = \frac{103 \cdot 5}{x + 0 \cdot 02}$,

$$4x + 0 \cdot 08 = 103 \cdot 5 \text{ or } x = \mathbf{25 \cdot 854 \text{ ohms.}}$$

$$\text{Input during 15 hours} = \frac{EIh}{1000} = \frac{4 \times 110 \times 15}{1000} = 6 \cdot 6 \text{ kilowatt hours.}$$

$$\text{Cost} = 4 \times 6 \cdot 6 = \mathbf{26 \cdot 4d.}$$

Heat loss in resistance $= I^2R = 4^2 \times 25 \cdot 854 = 413 \cdot 68$ watts.

$$\text{Percentage loss} = \frac{\text{heat loss} \times 100}{\text{watts supplied}} = \frac{41{,}368}{440} = 94\%.$$

This method of charging accumulators is extremely wasteful, and can only be countenanced on the grounds of simplicity and convenience.

Example 4. *A compound wound dynamo gives a current of* 120 *amp. at a terminal p.d. of* 230. *Find the efficiency if the field current is* 6 *amp., armature resistance* 0·09 *ohms and the series resistance* 0·04 *ohms.*

Armature current $= 120 + 6 = 126 \text{ amp.} = I_a$.

Watts loss in field $= 230 \times 6 = 1380$ watts.

Watts loss in armature $= I_a^2 R_a = 126^2 \times 0 \cdot 09$
$= 1429$ watts.

Watts loss in series $= I^2 R_s = 120^2 \times 0 \cdot 04 = 576$ watts.

Total loss $= 3385$ watts.

$$\text{Efficiency} = \frac{\text{watts generated}}{\text{watts generated} + \text{loss}}$$

$$= \frac{230 \times 120}{230 \times 120 + 3385} = \frac{27{,}600}{30{,}985}$$

$$= 89 \cdot 06\%.$$

$$\text{By formula. Efficiency} = \frac{VI}{I_a(V + I_a R_s + I_a R_a)}$$

$$= \frac{27{,}600}{126(230 + 126 \times 0 \cdot 04 + 126 \times 0 \cdot 09)}$$

$$= \frac{27{,}600}{126 \times 246 \cdot 38}$$

$$= \mathbf{88 \cdot 9\% \text{ approx.}}$$

Conversion of electrical to mechanical energy. This conversion is accomplished by employing an electric motor. In construction a motor is exactly like a dynamo but works in the reverse way,

current being supplied to the coils on the armature, which is set rotating and is then capable of doing mechanical work. The principle involved is shown in Fig. 183, where a conductor is conveying a current downwards; this current sets up a magnetic field which, in conjunction with that of the mag-

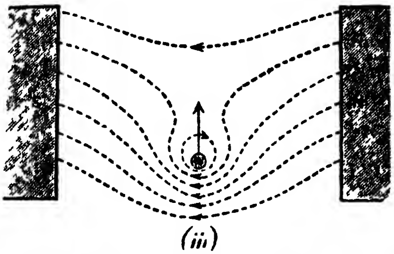


FIG. 183. The motor principle.

FIG. 184. Fleming's left hand rule.

nets, forms the resultant field shown in the diagram. The lines of force tend to straighten out, and in so doing set the conductor moving upwards. No motion will take place if the magnetic lines of force are parallel to the conductor. The force acting on the conductor will be a maximum when the axis of the conductor and the lines of force are at right angles. In any problem where the direction of motion is to be determined, **Fleming's left hand rule** (Fig. 184) is very useful. If the F*orefinger represents the direction of the magnetic field and the* m*I*ddle *finger the direction of the current I, then the* thuM*b will indicate the direction of motion or tendency for motion.*

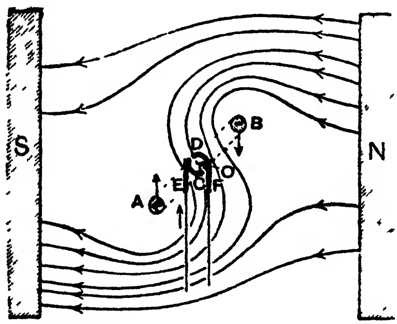


FIG. 185. The principle of the motor.

This rule may be applied to a single rectangular coil AB, the passage of a current producing clockwise rotation in a magnetic field (Fig. 185). Fixed metal brushes E and F feed the current through the

halves C and D of the split ring or commutator to the coil, in such a way that it flows alternately in opposite directions in each half of the coil, so that the tendency to rotate is continuously clockwise. The torque acting on the coil is a maximum when the coil is horizontal and zero when it is vertical, and a more uniform torque is obtained by providing a large number of coils wound on the same axle or armature. By shaping the pole pieces and making the armature of sheets or laminations of soft iron the magnetic flux is increased, because iron is substituted for air and the reluctance therefore decreased. As the number of coils increase so must the number of segments on the commutator, so that each coil may be fed with current going in the required direction.

Example 1. *It is required to raise* 18,000 *gallons of water per hour from a mine* 1000 *ft. below the surface. The combined efficiency of pump and direct current (D.C.) motor is* 60%. *If* 12% *of the input is lost in pipe friction, find the current necessary if* 500 *volts is maintained at the motor terminals.*

$$\text{Work to be done} = \frac{18{,}000 \times 1000 \times 10}{60} \text{ ft. lb. per min.}$$

$$= \frac{3{,}000{,}000}{33{,}000} \times 746 \text{ watts.}$$

$$\text{Input for motor} = \frac{746{,}000}{11} \times \frac{100}{60} \times \frac{100}{88} = 128{\cdot}44 \text{ kW.}$$

$$\therefore \text{ current} = \frac{128{,}440}{500} = 256{\cdot}8 \text{ amp.}$$

Back e.m.f. of a motor. Since the conductors of a motor are cutting lines of force, an e.m.f. is set up which tends to drive a current in the reverse direction to the current supplied to drive the motor. This e.m.f., which tends to reduce the current in the armature, is known as the back e.m.f., or e. It is obviously dependent upon the motor speed, and is very small when a motor starts. In these circumstances the resultant e.m.f. applied, namely $E-e$, is very great, and a large and damaging current would flow through the armature and ruin the insulation and any soldered joints. Hence the necessity for employing some form of starting resistance in series with the motor. As the motor starting handle is turned, the coils of this starting resistance may be cut

out one at a time, so that the current may be kept within reasonable limits until e grows with gathering speed.

In the case of a shunt generator the voltage and power equations are respectively,

$$V = E - I_a R_a \quad \text{and} \quad VI = EI - I_a^2 R_a \text{ (approx.)}.$$

Let the generator be connected to a supply the voltage of which is maintained by other generators. Assume V to rise until it has a value E. In this case $I_a R_a = 0$ and $I = 0$. Any further rise in the value of V will cause a current to flow in the opposite direction to that when the machine is acting as generator.

The voltage equation then becomes,

$$V = E + I_a R_a.$$

From the principles explained with electromagnetism it should be clearly understood that the reversed current will maintain the same direction of rotation in the armature.

Multiplying through by I, the power equation becomes

$$VI = EI + I_a^2 R_a \text{ (approx)}.$$

Of these quantities $I_a^2 R_a$ is the copper loss in the armature, and EI the electrical power equivalent of mechanical power. Of the latter, part is lost in friction, but the bulk is available for use at the motor shaft. E in this case is the back e.m.f. and is replaced by the symbol e.

Speed-load characteristics of motors. These may be deduced from the voltage equation $V = e + I_a R_a$.

As explained in the section on generators, the expression $K\phi N$ may be substituted for e, and then,

$$V = K\phi N + I_a R_a,$$

and

$$N = \frac{V - I_a R_a}{K\phi}.$$

Thus the speed N r.p.m. is inversely proportional to the total flux ϕ, while the change in speed is directly proportional to I_a.

Since $I_a R_a$ is only a small percentage of the value of V in modern machines, its effect may be neglected.

$$\therefore N \text{ varies as } \frac{1}{\phi}.$$

Series motor. Assuming that the total flux varies as I the load current, then N varies as $\frac{1}{I}$. Consequently the speed characteristic or the N *v.* I graph will be a rectangular hyperbola. In actual motors ϕ is not proportional to I over the whole range of load currents, but the general shape of characteristic is the same.

This type of machine is suitable for heavy maintained loads as in traction. Series motors should never be run on light load as the speed becomes excessive, and they should always start on load. In the section on electro-magnetism it was shown (p. 328) that the force acting on a conductor in a magnetic field was proportional, for a given displacement, to ϕI, but ϕ itself is proportional to I, hence the starting pull will be proportional to I^2. Thus series motors have good starting qualities and can be started under load.

Shunt motor. In this type of motor the flux ϕ is independent of I and only depends on V. On this account a shunt machine is practically a constant speed machine, the actual required speed being arranged by adjusting the field resistance R_f.

The speed characteristic, or N *v.* I graph, is a straight line, the speed decreasing slightly with increasing load and current. The speed increases with increasing field resistance.

At constant terminal voltage, N varies as $1/\phi$, the flux will increase with the field current and as the latter varies inversely as the field resistance, then,

N increases with R_f, the field resistance.

Also, since the pull at starting varies as ϕI and ϕ is constant.

$\therefore$ the starting pull varies as I.

Since a heavy starting load will need a heavy starting current, *shunt machines should never be started on load.*

Compound motor. This is a combination of the series and shunt types of machines. By virtue of the series windings this motor possesses good starting properties and is capable of dealing with heavy loads, especially of the intermittent type. The compound motor can also be run on light load, due to the possession of shunt winding, because racing is prevented at low loads. Motors of the

compound type are used when sudden loads are thrown on the motor as in rolling mills, etc. The actual speed characteristic depends upon the ratio of series to shunt windings (see Fig. 186).

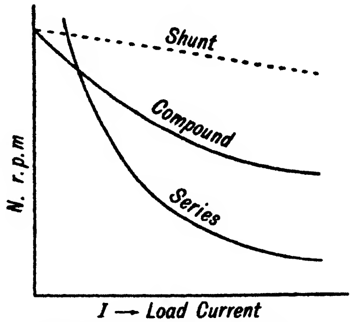


FIG. 186. Speed characteristics of motors.

Example 1. *A 30 B.H.P. shunt-wound motor receiving a constant e.m.f. of 200 volts at its terminals has an armature resistance of 0·052 ohm. The armature and field currents are 120 and 4·4 amp., and the loss in the field coils is 880 watts. Calculate the back e.m.f. and the electrical, commercial and mechanical efficiencies of the motor.*

$$e = \text{back e.m.f.} = E - I_a R_a$$
$$= 200 - 120 \times 0{\cdot}052 = 193{\cdot}76 \text{ volt.}$$

Watts in armature tending to produce rotation

$$= 120 \times 193{\cdot}76 = 23{,}251{\cdot}2 \text{ watts.}$$

Note that some of this power would be spent in overcoming armature iron losses and friction of bearings, etc.

Total current supplied $= 124{\cdot}4$ amp.

∴ Total watts supplied

$$= EI = 124{\cdot}4 \times 200 = 24{,}880 \text{ watts} = \text{electrical input.}$$

$$\text{Electrical efficiency} = \frac{23{,}251}{24{,}880} = 93{\cdot}44\%.$$

$$\text{Commercial efficiency} = \frac{\text{brake output}}{\text{electrical input}} = \frac{30 \times 746}{24{,}880} = 89{\cdot}9\%.$$

$$\text{Mechanical efficiency} = \frac{\text{commercial efficiency}}{\text{electrical efficiency}}$$
$$= \frac{89{\cdot}93}{93{\cdot}44} = 96{\cdot}25\%.$$

Example 2. *A shunt motor with supply voltage at 240 volts takes a full load armature current of 74 amp. The resistance of the armature when cold is 0·08 ohm. The supply company specify that the initial motor current shall not exceed 1·5 times the full load current. What resistance must be placed in series with the armature on starting the motor?*

1·5 times full load current $= 1{\cdot}5 \times 74$ or 111 amp.

On starting, the generated back e.m.f. is zero, and $V = I_a R_a$.

Now $V = 240$ volts, $I_a = 111$ amp. ∴ $R_a = \dfrac{V}{I_a} = \dfrac{240}{111} = 2{\cdot}16$ ohms.

2·16 ohms is the total armature resistance required, and taking into account the armature resistance

$$\text{series resistance required} = 2{\cdot}16 - 0{\cdot}08 = \mathbf{2{\cdot}08\ ohms.}$$

The resistance of the armature, 0·08 ohm, is very small in comparison with the 2·16 ohms and in practice is neglected.

Example 3. *In the case of the motor of Example 2, the normal full load speed is 950 r.p.m. It is required to reduce this to 500 r.p.m. while the motor is to exert the same torque. Determine the resistance required in the armature.*

$$\text{Back e.m.f. at 950 r.p.m.} = V - I_a R_a$$
$$= 240 - 74 \times 0{\cdot}08 = 234 \text{ volts.}$$

At 500 r.p.m., since the back e.m.f. is proportional to the speed, this will be reduced to $\frac{500}{950} \times 234$ or 123 volts, *i.e.* a drop of $234 - 123 = 111$ volts.

This voltage must be absorbed by the extra resistance placed in the armature circuit.

By Ohm's law, $$R = \frac{111}{74} = \mathbf{1{\cdot}5\ ohms.}$$

NOTE.—This method of speed reduction is very wasteful of energy, which is dissipated in heat in the resistance, and is a total loss.

$$\text{Loss} = I^2R = 74^2 \times 1{\cdot}5 = 8214 \text{ watts.}$$

$$\text{Percentage loss on input} = \frac{8214}{240 \times 74} \times 100 = \mathbf{46{\cdot}3\%}.$$

Example 4. *In the case of the motor of Example 2, the normal full load speed is 950 r.p.m. It is required to reduce this speed to 500 r.p.m. while the output of the motor is to be maintained constant. Determine the resistance required in the armature circuit.*

As in Example 3, the back e.m.f. at 950 r.p.m. = 234 volts.

At 500 r.p.m. this will be reduced to $\frac{500}{950} \times 234$ or 123 volts, *i.e.* the same drop is required as before.

$$\text{Output at 950 r.p.m.} = \text{output at 500 r.p.m.,}$$
$$\text{or } 74 \times 234 = 123 \times \text{new value of current } I.$$
$$I = 74 \times 234 \div 123 = 140{\cdot}8 \text{ amp.}$$

$$\text{Resistance required in armature} = \frac{\text{voltage drop}}{\text{current}}$$
$$= \frac{111}{140{\cdot}8} = \mathbf{0{\cdot}79\ ohm.}$$

Force between parallel conductors. Let two conductors A and B be very long and r cm. apart. Suppose currents are flowing in opposite directions along the conductors so that the force acting between them is one of repulsion.

It has been shown that the field strength H at a radial distance r from the centre of a long conductor is

$$H=\frac{2I'}{r}.$$

$\therefore$ the conductor B, say, will be in a field of strength $\frac{2I'}{r}$, due to A, when the latter carries a current of I' absolute units.

The force per unit length (from the relation $HI'l$)

$$=HI'=\frac{2I'}{r}\times I'=\frac{2(I')^2}{r} \text{ dynes.}$$

Thus the force increases as the square of the current.

The force on a pair of conductors for a length l cm.

$$=\frac{2(I')^2 l}{r} \text{ dynes.}$$

The above has an important application in the design of electrical machines. When conductors are placed close together as in the winding of machines, r is very small, and as the force increases as the square of the current, very high stresses may be set up when very heavy or abnormal currents flow. Such currents occur in short circuits. For this reason, in large machines the windings are clamped to prevent displacement.

EXERCISES ON CHAPTER VIII

Generation of an e.m.f and generators.

1. Explain briefly the method of generating an e.m.f. in a conductor by mechanical means.

2. Explain Fleming's Right Hand Rule.
Show that the e.m f. generated or induced in a conductor depends upon the rate of cutting of the lines of force.

3. State Lenz's law and describe a simple experiment which demonstrates it.

4. Explain briefly the principle of the dynamo, and sketch the magnetic circuit for a 4-pole machine.

5. Explain the essential differences between the shunt and series wound dynamos. What is a compound wound dynamo ?

6. Determine the electrical and commercial efficiencies of a series dynamo from the following results of a test :

Resistance of dynamo, 0·06 ohm ; p.d. at terminals, 110 volts ; current in external circuit, 122 amp. ; power supplied, 21 H.P.

7. An internal combustion engine of $10\frac{1}{2}$ I.H.P. is used to drive a dynamo which maintains a p.d. of 110 volts at its terminals when the current generated is 39 amp. If the mechanical efficiency of the engine is 75%, determine the commercial efficiency of the dynamo.

8. Find the commercial efficiency of a dynamo when driven by a 100 B.H.P. engine if the dynamo sends a current of 24 amp. through an external circuit of resistance 105 ohms.

9. If the commercial efficiency of a dynamo is 78% determine the B.H.P. required for a prime mover to drive the dynamo and maintain an output of 70 kW. in the external circuit.

10. The field winding resistance of a motor-car dynamo is 12·5 ohms at 20° C. and 16·33 ohms at 100° C.

Calculate the temperature coefficient of the winding. What will the resistance of the winding be at 0° C.

11. Calculate the rise in temperature of a shunt field winding with copper wire if the resistance increases 18% on load. Take the temperature coefficient of copper as 0·4% per cm. degree.

12. Calculate the watts loss in the generator and the electrical efficiency of a shunt wound dynamo from the following data :

Current in external circuit, 125 amp. ; p.d. across terminals, 205 volts ; resistance of armature and field coils, 0·06 and 38 ohms respectively.

13. Determine the efficiency of a compound wound dynamo from the data given below :

Current in external circuit, 100 amp. ; p.d. across terminals, 200 volts ; field current, 5 amp. ; armature resistance, 0·07 ohm ; series resistance, 0·04 ohms.

14. The output of a shunt dynamo is 15 kW., and the terminal p.d. is 110 volts. The field and armature resistances are respectively 80 ohms and 0·05 ohm. Calculate the armature and field currents, the watts loss in the dynamo and the electrical efficiency.

15. Explain briefly the methods employed in separate and self-excited generators to build up the necessary magnetic flux.

16. By means of line diagrams show how the various essential parts of series wound, shunt wound and compound wound dynamos are linked together.

17. With the aid of diagrams show the nature of the voltage-load current characteristics for the three main types of dynamo. What are the meanings of the terms, *level compound generator* and *over-compounded generator?*

18. A pump raises 2000 gallons of water to a height of 300 ft. in a pumping time of $1\frac{1}{2}$ min. Find the B.H.P. of a motor driving the pump, and the current taken on 440 volt supply.

19. Calculate the cost of working per day of 8 hours a motor taking 25 amperes on a 230 volt supply if the motor has an efficiency of 90% and the price of power per unit is 1d.

20. A motor drives a pulley 3 ft. diameter at 300 r.p.m. The difference in tensions on the belt is 220 lb. and the motor efficiency is 90%. Find the cost of running for 8 hours at $1\frac{1}{4}$d. per unit and the current taken at 400 volts.

21. A motor driven centrifugal pump is used to fill a storage tank for a mill. The pump is 8 ft. above the level of a river while the storage tank is 30 ft. above the level of the pump. Calculate the H.P. of the motor if its efficiency is 80%, the delivery is to be 2500 gallons per minute and the combined efficiency of pump and pipe line 70%.

22. A 28 B.H.P. shunt wound motor supplied with a constant p.d. of 240 volts across its terminals has an armature resistance of 0·06 ohm. The field and armature currents are respectively 2·5 amp. and 100 amp. Calculate (*a*) the back e.m.f.,
(*b*) the electrical, mechanical and commercial efficiencies.

23. An ore hoist for a steel works has a capacity of $2\frac{1}{2}$ tons and a counter weight is used to balance the weight of the lift and half the capacity. Assuming an efficiency of 50% for the gears and motor, and a lifting speed of 240 ft. per min., determine the necessary B.H.P. of the motor.

24. A shunt motor with supply voltage at 240 volts takes a full load armature current of 84 amp. while the armature resistance when cold is 0·075 ohm. The normal full load speed is 1050 r.p.m. Assuming a starting current 1·5 times the full load current, calculate
(*a*) the series resistance with the armature required on starting,
(*b*) the back e.m.f. of the motor.

25. In the motor of Question 24, the speed is to be reduced to 600 r.p.m. Calculate the additional armature resistance required if,
(*a*) the same torque is to be exerted, and
(*b*) the same output is required.

26. A series motor is supplied with 120 amp. at a p.d. of 110 volts. If the electrical efficiency of the motor is 90% and the watts loss is 380 watts, calculate the back e.m.f. of the motor, its B.H.P. and its commercial efficiency.

27. What do you understand by the term, *back e.m.f.*?

Determine the back e.m.f. of a series motor when the speed is such that a current of 50 amp. is supplied at a constant p.d. of 110 volts. Armature resistance 0·12 ohm.

28. The following observations were recorded in the case of a tramcar motor:

Current supply, 74 amp.; constant p.d. at terminals, 500 volts; car speed, 12 m.p.h.; B.H.P. of motor, 42; car wheels, 33 in. in diameter; gear ratio, 4·2 : 1.

Calculate (*a*) the armature speed in r.p.m.,
(*b*) the tractive effort at the tramcar wheels,
(*c*) the overall efficiency of motor and gears.

29. Explain the relative merits and demerits of series wound, shunt wound and compound wound motors and show on a graph their speed-load characteristics.

CHAPTER IX

ELECTRICAL MEASURING INSTRUMENTS

THE principles dealt with in the preceding chapters have further application in the design of instruments for the direct measurement of current, pressure and energy. The scales of standard instruments are marked or calibrated in the units and subdivisions according to the rigid standard set up in the practical definition of those units. These standard instruments can be periodically checked at the National Physical Laboratory at Teddington, and used in the calibration of instruments made for experimental and commercial work.

Instruments employed to *detect* qualitative features, but not quantitative, such as charges of electricity, or the presence of an electric current, have usually the suffix *scope*, as for example, electroscope, galvanoscope. The suffix *meter* is given to the names of instruments employed in the *measurement* of quantity or size of currents or potential differences, as for example, galvanometers, ammeters, voltmeters. Most of these meters indicate their readings by a pointer or beam of light moving over a calibrated scale, the motion being produced by the forces set up by the pressure or current to be measured. This motion is controlled by a variable force resist-

ing the action of the pressure or current until a position of equilibrium is obtained. A control is necessary to make the exciting force measurable and to make a larger pressure or current give a larger deflection on the instrument scale. The **controlling force or control** may be effected by gravity, a spring, torsion of a wire, the earth's magnetic field, or some artificial and known magnetic field. It is very necessary for this position of equilibrium to be reached quickly, without violent oscillations, and a damping device is usually introduced to achieve this object. An instrument which soon reaches the equilibrium position is said to be **deadbeat,** or a deadbeat type of instrument.

The main features of the principal types of measuring instruments will now be discussed. Galvanometers are employed for measuring small currents and pressures, while larger quantities can be measured with ammeters and voltmeters respectively. These instruments may be classified under the headings of **moving coil** and **moving iron** instruments. In the first type, a coil carrying the current to be measured is deflected in the field of a permanent magnet; and in the second type, a temporary soft iron magnet is deflected in the field of a fixed coil which carries the current to be measured.

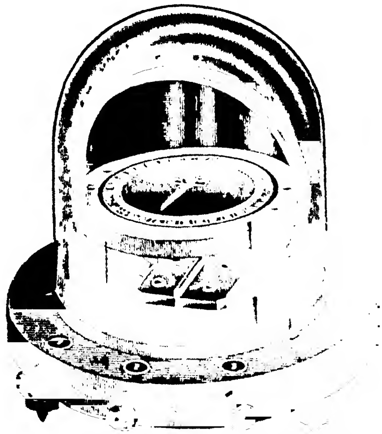


Fig. 187. Tangent galvanometer.

The tangent galvanometer. This instrument possesses a small moving magnet suspended at the centre of a circular coil of large radius having one or more turns. The current to be measured flows through the coil and sets up a uniform magnetic field in the neighbourhood of the magnet, which is small in comparison with the coil. Fig. 187 shows a form of tangent galvanometer made by Messrs. Philip Harris & Co., Ltd. It is provided with a mahogany base and levelling screws, this base supporting a split brass ring insulated from the base by ebonite. This brass

ring acts as a low resistance coil (0·02 ohm), and it is connected to two of the terminals shown. A coil of higher resistance (0·2 ohm) may be used instead, and this consists of 10 turns of double silk-covered wire (No. 22) wound on the brass ring and connected to the high resistance terminals. The needle is provided with an agate centre, which is supported on a pointed steel spindle to lessen friction. A pointer fixed at right angles to the magnet moves over a scale graduated in degrees, and this pointer is made of aluminium and designed to make the instrument deadbeat, air friction providing the damping effect. The glass shade keeps the coils, needle and dial free from dust, and prevents the readings being affected by air currents.

When using this instrument it is important that the plane of the coil shall be parallel to the earth's magnetic field, so that when no current is flowing the needle will lie in the magnetic meridian with its axis in the plane of the coil. When the current I' flows, the magnetic force due to it will act at right angles to the magnetic N. and S. axis, and therefore at right angles to the earth's field, and the forces acting on the poles of the magnet will be as shown in Fig. 188, if I' is measured in absolute units.

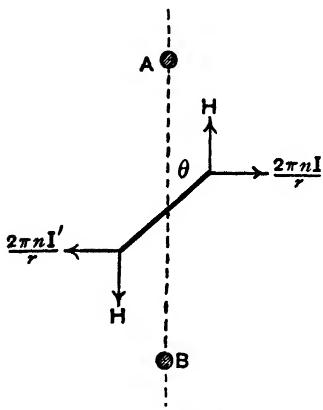


FIG. 188. Forces acting for tangent galvanometer.

Assuming the magnet is of unit length and pole strength m, the force, due to the current I', acting on the poles is $\frac{2\pi n I' m}{r}$, where r cm. is the mean radius of the n coils. Then if the deflection is θ degrees, the couple due to earth's field of strength H = couple due to the magnetic effect of the current.

$$Hm \sin\theta = \frac{2\pi n I' m}{r} \cos\theta, \text{ and since } \tan\theta = \frac{\sin\theta}{\cos\theta}$$

$$I' = \frac{Hr}{2\pi n} \tan\theta,$$

$$= k \tan\theta.$$

k is called the **constant or reduction factor of the galvanometer.** H is the horizontal component of the earth's field, and is measured in gauss or lines per sq. cm. $k = \dfrac{10Hr}{2\pi n}$ if the current is to be measured in amperes, and it can be calculated if H, r and n are known ; or it can be found by comparing the galvanometer reading with that of a standard instrument or an ammeter. When strong currents have to be measured the low resistance coil should be employed, and the high resistance coils for the weaker currents.

Example 1. *In an expt. to find the constant for a galvanometer* 2·3 *grams of copper were deposited on the cathode by electrolysis in* 1 *hour by a current which gave an average galvanometer deflection of* 41·2°. *Given that a current of* 1 *amp. deposits* 0·0003294 *gram of copper per second, find the constant of the galvanometer.*

$$I = \text{strength of current} = \frac{2 \cdot 3}{3600 \times 0 \cdot 0003294} = 1 \cdot 939 \text{ amp.}$$

Now
$$I = k \tan 41 \cdot 2^\circ ;$$
$$\therefore\ k = \frac{I}{\tan 41 \cdot 2} = \frac{1 \cdot 939}{0 \cdot 8754} = 1 \cdot 355.$$

This example illustrates also the method of measuring the strength of a current by its electrolytic effect.

Example 2. *A tangent galvanometer gave a reading of* 26° *for a current of* 0·6 *amp. through one set of its coils. What is the constant for the galvanometer for this set ? What would the current be for a reading of* 63° *?*

In first case, $k = \dfrac{I}{\tan \theta} = \dfrac{0 \cdot 6}{\tan 26^\circ} = \dfrac{0 \cdot 6}{0 \cdot 4877} = 1 \cdot 23.$

In second case, $I = k \tan \theta = 1 \cdot 23 \times \tan 63^\circ = 1 \cdot 23 \times 1 \cdot 9626$
$= \mathbf{2 \cdot 414}$ **amp.**

Example 3. *Find the value of the constant for a tangent galvanometer if* $H = 0 \cdot 18$ *lines per sq. cm. and it has* 10 *coils of* 0·028 *in. diameter wire, the mean diameter of the coils being* 11·5 *cm. What is the strength of the field at the centre of the coil if the current is* 2 *amp. ?*

The constant $k = \dfrac{10Hr}{2\pi n} = \dfrac{10 \times 0 \cdot 18 \times 11 \cdot 5}{2 \times \pi \times 10 \times 2}$

$= \mathbf{0 \cdot 1647}$. **Ans. when current is in amperes.**

$k = \mathbf{0 \cdot 01647}$ **when current is in C.G.S. units.**

Strength of field $= \dfrac{2\pi TI}{10r} = \dfrac{2\pi \times 10 \times 2}{10 \times 6 \cdot 75} = \mathbf{1 \cdot 862}$ **gauss.**

Suspended coil galvanometer. These instruments, using a suspended coil instead of a suspended or pivoted magnet, are being increasingly favoured. In principle their action depends upon the influence of a permanent magnet on the rectangular or circular coils of a conductor through which a current is flowing. The coil CC (Fig. 189 (*a*)) is hung by a fine phosphor bronze strip F, which serves to convey the current to the coil. A small mirror is usually fixed to the suspension F, so that a beam of light from an external lamp may be reflected upon a screen having a scale marked on it, the arrangement lending itself to accurate and sensitive measurement. Actually the image of a fine hair or scratch, on the lens of the projecting lantern,

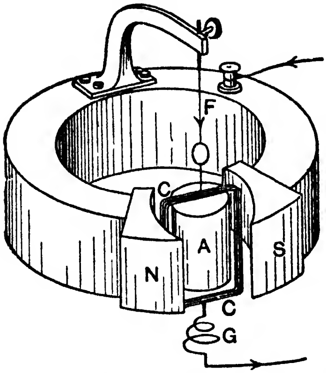


FIG. 189 (*a*). Coil and pole pieces of a suspended coil galvanometer.

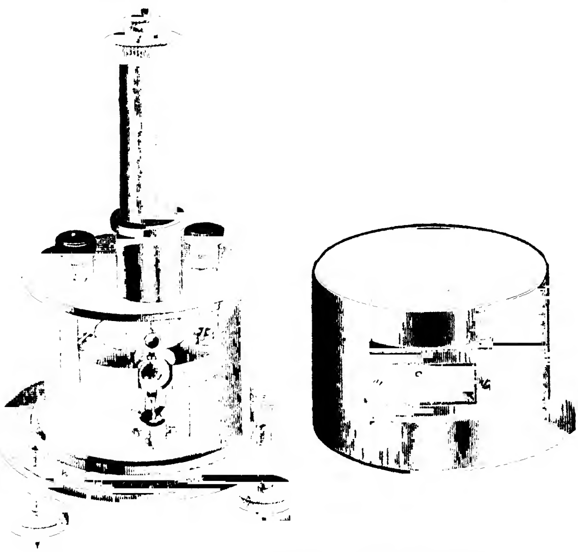


FIG. 189 (*b*). Suspended coil galvanometer.

is reflected and focussed on the screen. The magnetic field is radial between the curved pole pieces and the soft iron cylinder A (Fig. 190), and when the current passes into the coil the latter is deflected and moves in the cylindrical space allowed for it. Control is effected by the torsion of the strip F producing an opposing couple to that due to the magnetic effect of the current. The turning moment on the coil varies directly as the strength of the current, the number of turns in the coil and the intensity of the magnetic field in which the coil moves. The latter, owing to the field being radial and concentrated, is practically constant. Hence the current will be directly proportional to the deflection, and consequently the scale of the instrument will have equal divisions over a wide range. This instrument also has the advantage that it is not affected by the earth's field or by the presence of magnets. Current leaves the coil through the loosely coiled strip G. When the coil is wound upon a metal spool or former, the eddy currents set up in the metal of the spool when it cuts the lines of force tend to oppose motion, and make the instrument deadbeat. In some suspended coil galvanometers a pointer is also provided which moves over a calibrated scale. The complete instrument is shown in Fig. 189 (*b*).

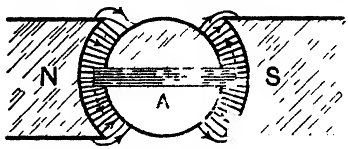


FIG. 190. Magnetic field of galvanometer.

Ammeters or Ampere meters and voltmeters. Moving coil instruments. Moving coil ammeters and voltmeters are both designed on the same principles, namely, those of the suspended coil galvanometer. The interaction between the magnetic fields due to the permanent magnet and the current causes a deflection of the coil, and in ammeters and voltmeters this deflection is usually resisted by the action of coil springs instead of the torsion of the suspension wire as with the galvanometer. By using coil springs as control, the instruments can be made more compact. The moving coil carries a comparatively long light pointer which moves over a graduated scale, enabling the magnitude of the current, or pressure, to be read directly in amperes or volts or in fractions of these. Moving coil instruments cannot be used for the measurement of alternating current.

The principal difference between ammeters and voltmeters of the type being described lies in the fact that ammeters must have a low resistance and voltmeters a high resistance. Since the current to be measured passes through the ammeter, a low resistance will not greatly reduce the value of the current in the circuit and the reading will be fairly accurate. On the other hand, a voltmeter, since it must be placed directly across the points where the potential difference is required, must have a high resistance to prevent a large current flowing through the instrument, which would alter the whole nature of the circuit and make the voltage reading misleading. The ammeter coil is therefore made of a few turns of relatively large diameter and low resistance wire, while that of the voltmeter is made of a large number of turns of fine wire. In addition, a voltmeter has often a high resistance put in series with its moving coil, either within the instrument or connected externally with it.

Large currents can always be measured as illustrated by the Example, p. 297, by placing a very low resistance in parallel with the ammeter, i.e. by using a shunt. Excessive heating should always be avoided in any measuring instrument since the resistance of an ammeter is low and that of a voltmeter high, and the ammeter is placed in series and the voltmeter in parallel with the portion of the circuit concerned, the risk of over-heating is decreased.

Fig. 191 shows a unipivot milliammeter one pole piece of which has been removed to show the nature of the suspension of the coil,

FIG. 191. Unipivot milliammeter.

which is of circular form. The coil is supported by a vertical steel spindle, having a fine pivot, resting upon an agate cup or jewel

bearing, situated in the centre of the soft iron core or keeper. The latter serves to increase the retentivity of the permanent magnet, and provides a single, almost frictionless, support to all the moving parts of the instrument. A spiral spring concentric with the vertical spindle and situated just above the pointer serves as a control for the instrument and acts as a link in passing the current to the coil, the current leaving by the loosely coiled wire below the soft iron sphere. The pointer of the instrument is clamped to the vertical steel spindle, and the whole of the moving parts are so adjusted that their centre of gravity coincides with the position of support. If the weight of the moving coil can be taken off the pivot when the instrument is not in use, or is being moved, there is much less likelihood of damage being done to the pivot and bearing. The instrument can be made deadbeat by winding the coil on a metal former, as with the suspended coil galvanometer, when the eddy currents set up in the former act as a damping device on the coil.

Moving iron instruments. These instruments can be used either as voltmeters or ammeters by adjustment of their resistances, and also for direct or alternating current circuits. The control is effected by spring or by gravity, that of the instrument now to be described being by gravity. Fig. 192 illustrates the skeleton arrangement of the instrument. Two soft iron rods, AB and GH, both parallel to the axis of the solenoid in which they are placed, become magnetised by induction when a current passes through the solenoid. Whatever the direction of the current, the poles A and G will repel each other because they will always have the same polarity. In a similar way repulsion occurs between B and H, and the combined action at each end causes the rod AB to swing away and rotate about its axis CD, which turns in jewelled bearings. The movement produces a motion of the pointer DE over the

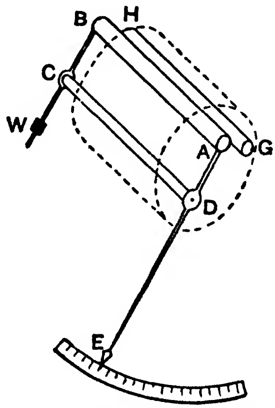


FIG. 192. Soft iron ammeter of the repulsion type.

graduated scale. The graduations on this scale are made by comparing the readings of the instrument with those of a standard.

Weight W provides the gravity control for this type of instrument, its initial position being such as to give zero reading with no current in the solenoid. When the weight is lifted more and more from its lowest position, due to increasing current and repulsion between the temporary soft iron magnets, the weight provides an increasing restoring moment, but not a uniformly increasing one. This means that a moving iron instrument has a scale which is non-uniform, the divisions being closer at the ends than in the centre. Damping is effected by a loosely fitting piston working in a cylinder containing air.

Another form of moving iron instrument operates on the principle of induction and attraction. An oval-shaped piece of soft iron pivoted eccentrically becomes more and more attracted and drawn towards a solenoid in which the current to be measured flows. The deflection is recorded by a pointer moving over a scale, control being effected by a spiral spring.

No shunt is used for moving iron instruments, the current passing directly to the solenoid, which consists of a few turns of thick wire for heavy currents and a large number of turns of fine wire for light currents. Care must be taken that the appropriate pair of terminals are selected.

Instruments which may be used either as voltmeters or ammeters can be manufactured so that the same size of parts can be used for each instrument over a wide range of measurement, if provision is made for incorporating series and shunt resistances in the instruments themselves. A change of coil or solenoid and a change of scale will also quickly adapt an instrument to read voltages or currents as required. A selection of terminals can be fitted to enable the operator to use the instrument either as a voltmeter in parallel or as an ammeter in series.

Hot wire ammeters and voltmeters. These instruments work on the principle that when a current passes along a wire, the temperature of the wire rises and it lengthens. If the ends are fixed, as far as possible the wire will sag. This sag is taken up by a fine wire or fibre attached to the centre of the heated wire. The fibre is passed round a pulley on the spindle carrying the pointer, and then fastened

to a stretched spring which keeps the fibre taut. As the hot wire sags the fibre is pulled forward and its motion communicated to the pulley and pointer. The pointer spindle is mounted in jewelled bearings, and as the moving fibre rotates the pulley fixed to the spindle, the pointer is made to move over a calibrated scale. In the case of the ammeter, a shunt is used to carry the main current to be measured, so that only a small portion flows along the wire to be heated. The hot wire ammeter can be used for measuring alternating current since the heating effect will be independent of the direction of flow; the value obtained is the virtual current, that is, the direct current which has the same heating effect as the alternating current which is passing.

The voltmeters are similar to the ammeters, except that the hot wire is made thinner and a resistance is put in series with this hot wire, instead of employing a shunt. The instruments are made deadbeat by mounting upon the pointer spindle an aluminium disc, which, when the pointer is deflected, moves between the poles of a permanent magnet.

These instruments have the advantages that (*a*) heating effects do not cause reading errors, (*b*) the absence of moving iron and coils do not produce errors due to induction, (*c*) they can be used for either direct or alternating current, and (*d*) they are unaffected by external magnetic fields or the effects of conductors.

Their chief disadvantages lie in the fact that the wire may be easily fused by excess current, and there is a lag in obtaining the maximum reading, which in some instruments may make the energy absorbed appreciable.

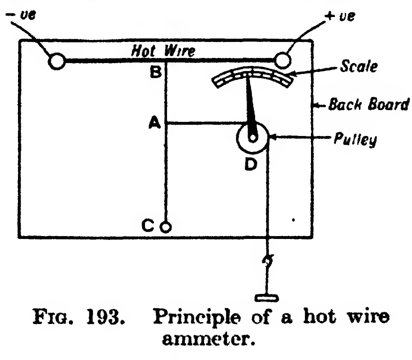


FIG. 193. Principle of a hot wire ammeter.

EXPT. 55.

OBJECT. *To show the principle of the hot wire ammeter.*

APPARATUS. Attached to a suitable back board (Fig. 193) are two terminals between which is tightly stretched a length of resist-

ance wire. From the mid-point B a cord is stretched and secured at C, and a further cord taken from a free loop at A and wound several times around the pulley D. To D is fastened a pointer indicating on a scale drawn upon the board. A light weight is fastened to the cord, which passes round the pulley D.

METHOD OF PROCEDURE. Pass a current from several dry cells through the resistance wire, when, due to heating and expansion, the point B will fall, thus causing a slackening of the cord BC, which is taken up at A, by the rotation of the pulley D. The pointer will register, on the scale, a deflection due to the passage of the current through the wire. Break the circuit and allow the wire to cool, when the pointer will be restored to its original position.

Example 1. *A voltmeter is connected in parallel with a resistance, while an ammeter is connected so as to read the current passing in both. The voltmeter indicates 45 volts and the ammeter 6·5 amp. What is the ohmic value of the resistance?*

$$\text{By Ohm's law, } I = \frac{E}{R}; \text{ or } R = \frac{E}{I} = \frac{45}{6 \cdot 5} = \mathbf{6 \cdot 923 \text{ ohms.}}$$

Example 2. *The maximum reading of an ammeter is 5 amperes and its resistance is 0·03 ohms. What shunt would be necessary to allow the instrument to read up to 60 amperes?*

If $\frac{1}{n}$ is the fraction of the whole current passing through the instrument (see p. 297), and $\frac{1}{n} = \frac{5}{60} = \frac{1}{12}$, then

$$\text{resistance of shunt} = \frac{1}{n-1} \times \text{resistance of instrument}$$

$$= \frac{1}{12-1} \times 0 \cdot 03 = \mathbf{0 \cdot 00273 \text{ ohms.}}$$

Example 3. *Find the resistance to be added in series to the coil of an ammeter, which has a maximum reading of 20 milliamperes and a resistance of 7 ohms, to enable the instrument to record voltages up to 500. If with this added resistance the ammeter records 18 milliamperes, what is the value of the p.d. being measured.*

The maximum current $= 0 \cdot 02$ amp.

" " voltage $= 500$.

$$\therefore \text{ total resistance } = \frac{E}{I} = \frac{500}{0 \cdot 02} = 25{,}000 \text{ ohms.}$$

$$\text{Resistance to be added } = 25{,}000 - 7 = \mathbf{24{,}993 \text{ ohms.}}$$

With this added resistance a reading of 20 milliamperes corresponds to 500 volts. Hence a reading of 18 corresponds to a voltage of $\frac{18}{20}$ of 500 or **450 volts.**

Example 4. *An ammeter and voltmeter are used to determine the internal resistance of a cell, and the voltmeter reading when the cell is on open circuit (i.e. no external circuit) is* 1·65 *volts. When an ammeter is connected in series with a resistance in the external circuit the voltmeter reads* 1·2 *volts and the ammeter* 1·86 *amperes. Find the internal resistance of the cell. What is the external resistance in ohms? Neglect the effects of the two instruments on the circuit.*

e.m.f. of cell = 1·65 volts = voltmeter reading when on open circuit.

$$R_i + R_e = \text{total resistance of circuit} = \frac{E}{I} = \frac{1{\cdot}65}{1{\cdot}86} = 0{\cdot}887 \text{ ohm.}$$

$$R_e = \frac{\text{p.d.}}{I} = \frac{1{\cdot}2}{1{\cdot}86} = \mathbf{0{\cdot}645 \text{ ohm.}}$$

$$\therefore\ R_i = \text{internal resistance of cell} = \mathbf{0{\cdot}24 \text{ ohm.}}$$

The Grassot fluxmeter. This is an instrument (Fig. 194) specially designed for investigating the strength and nature of magnetic fields.

Fig. 194. Grassot fluxmeter.

The fluxmeter consists of a suspended coil galvanometer of the ballistic type, that is, it is specially constructed to read currents of short

duration. To attain this end the moving parts must be heavy and the damping as small as possible, while the control constant is also very small. The instrument thus possesses the property that the indications given by the pointer are determined solely by the total quantity of electricity discharged through the suspended coil, and are almost independent of the rate at which the discharge takes place. A search coil is provided for the instrument, and if it is connected to the terminals of the fluxmeter, any movement of this coil in a magnetic field which brings about a change in the number of magnetic lines of force linked with it will produce a deflection of the fluxmeter pointer. This deflection will be proportional to the charge induced, which is in turn proportional to the total change in the lines of force interlinked with the coil. The pointer will remain at the extreme limit of its deflection sufficiently long for a reading to be made. Since the rate of cutting the lines of force does not affect the readings over a wide range, and the number which are cut does, the instrument fulfils admirably the purpose for which it is designed. The rate of cutting would be difficult to maintain constant, and it is fortunate that it has little effect on the results.

Alternating currents. It is not possible in the scope of this book to deal at any length with the alternating current or A.C. circuit. At the same time, with the increasing and almost general use of A.C., it is desirable that some introductory work be discussed. It has been shown that a change in magnetic flux in link with a circuit is productive of an electromotive force in the circuit. This electromotive force will have a magnitude depending on the rate of change of magnetic flux and it will tend to produce a reactionary current opposing this change of flux. Thus, if a conductor is permitted to revolve between two soft iron poles, the rate of change of flux will vary according to the approach or recess of the coil from the poles (Fig. 195). In this way a variable e.m.f. is set up, varying between a positive maximum through zero to a negative maximum as the coil rotates.

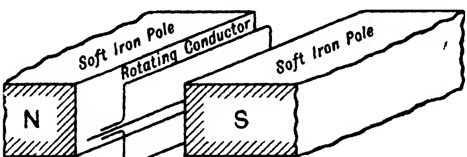


FIG. 195. Generation of an alternating current.

It will be seen that this is a periodic change and the **period** or **cycle** is completed when the change from positive to the next condition of positive e.m.f. is made.

Frequency is the name given to the number of these complete periods or cycles which occur in one second. An illustration of these terms may be taken from the diagram obtained from a Fletcher Trolley when the Trolley is moving with uniform velocity (Fig. 196),

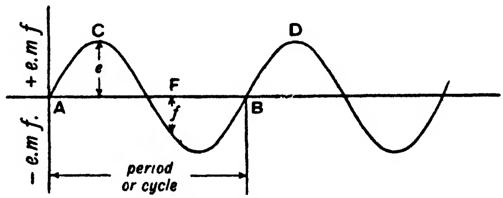


FIG. 196. Simple case of variation of an alternating e.m.f.

in which *AB* or *CD* is the period or cycle; if the vibrator is moving at 5 oscillations per second the frequency is 5. It is a similar curve to this which shows the e.m.f. against the period or time of a cycle for an A.C. current, and the vertical ordinate shows the e.m.f. generated at that point in the cycle. For example, e.m.f. at C $= e$ and at F the e.m.f. $= f$ to the scale to which the drawing is made. It will be noticed that the e.m.f. at F is opposite to that at C, and is referred to as a negative e.m.f. Any generator of A.C. produces a varying e.m.f. as shown, but a very high frequency is developed, so that over a period of time the crests *C* and *D* are very close together, and an impression of a continuous e.m.f. persists. The actual production of this curve from any machine can be obtained by the use of a cathode ray or moving coil type of oscillograph, and the development of this instrument has made it possible for an engineer to examine the performance of an A.C. machine at all stages in its cycle. The oscillograph has also been adapted to indicate the performance of high-speed I.C. engines, where the cylinder pressures may be recorded at all points in a rotation or period in the I.C. cycle.

Except for the hot wire ammeter, the instruments covered in this chapter are unsuitable for the measurement of alternating currents. They can be converted to this use by the incorporation of a metal

or other rectifier which converts the A.C. to D.C. and allows the A.C. to be measured through its D.C. conversion. Thus the equivalent direct current is measured in this type of instrument, a type which is achieving popularity.

The oscillograph. The oscillograph is an instrument which is coming into general use for a variety of purposes, particularly in the study of the instantaneous values of quantities that are varying continuously with time. The alternating current is an example of such a varying quantity and some typical oscillograph diagrams for an alternating current are shown in Fig. 197. These

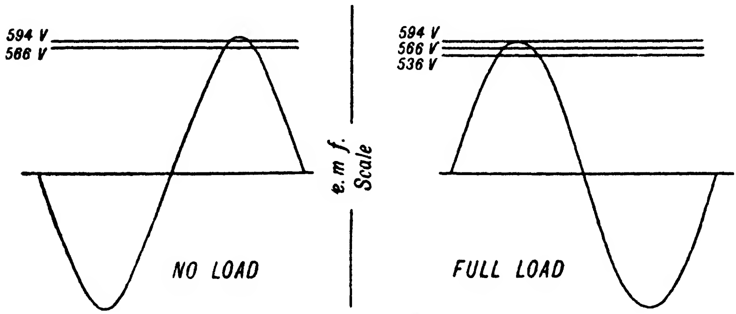


FIG. 197. Typical oscillograms.

diagrams are known as oscillograms and it can be seen that the variation of e.m.f. with time is clearly shown throughout the cycle or period.

There are two types of oscillograph in general use, the Duddell moving coil type and the cathode ray type, the latter of which is superseding the former even in low-frequency work.

The Duddell oscillograph. The usual type of moving coil instrument cannot be used on alternating current, because with each alternation of the current flowing through the coil its polarity and hence the rotating torque on the coil is reversed. In consequence the pointer remains stationary under the action of the rapidly reversing torque. If, however, the coil is made extremely light and the pointer replaced by a small mirror, so that the inertia of the moving parts is reduced to a minimum, then such a coil will oscillate to and fro with the reversals of current flowing through it, and the spot

of light thrown on to a screen by the reflecting mirror and a lamp will extend to a line the length of which will be proportional to the amplitude of the current flowing through the coil. Now if the screen on which the oscillating spot of light falls is given a steady motion at right angles to the line traced by the spot, this line would become a wavy curve similar to those shown in Fig. 197.

Such a curve is called the **wave form** of the alternating current, because it is, in effect, a graph of current against time. From this graph the instantaneous value of the current in the coil at any particular time can be determined, and, if necessary, photographed and measured. In actual practice the curve is obtained, not by moving a screen, but by projecting the spot of light on to a drum, carrying a number of plane mirrors on its circumference, and revolving at a uniform speed on an axis lying in the plane of the oscillating light beam from the moving coil.

The cathode ray oscillograph. In this type the wave form is developed in a similar manner to the moving coil type, that is, by giving to a beam of light two motions at right angles, one having a uniform velocity and the other a vibrating motion supplied by the alternations of the A.C. being tested. Fig. 198 illustrates the opera-

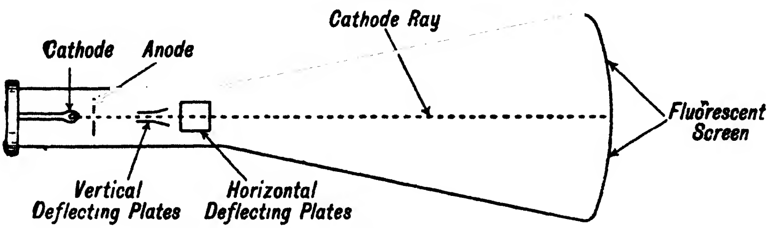


FIG. 198. The cathode ray tube.

tion and construction of a cathode ray tube, which is the important part of this oscillograph. It consists of a number of electrodes contained in an evacuated glass tube. In Fig. 198 the cathode is heated by passing a current through it, upon which it emits electrons like the filament of a radio valve. The electrons are attracted towards the anode, which is maintained at a high positive potential. Some of these electrons strike the anode and others go through the small hole that is pierced in the middle of the anode and proceed down

the tube with a high velocity, going between two separate pairs of electrodes called the deflecting plates, to strike the fluorescent screen fitted to the large end of the tube. This beam of electrons is the cathode ray which provides the bright spot of light on the screen.

If an alternating potential is applied to the vertical deflecting plates the beam of electrons will oscillate in a vertical plane, being alternately attracted and repelled from each electrode in turn, and the spot of light on the screen will extend to a vertical line. If, at the same time, the two horizontal deflecting plates are given a uniformly increasing potential difference, the vertically oscillating beam will be steadily moved horizontally and the trace of the end of the light beam will be the wave form of the alternating potential applied to the vertical deflecting plates. The potential difference between the horizontal deflecting plates cannot be increased indefinitely, and, in practice, it is quickly returned to zero at regular intervals to repeat the process. If this is done sufficiently rapidly, and at the correct time, the result, to the eye, is an apparently continuous curve.

The mechanism which arranges for the p.d. between the horizontal deflecting plates to rise steadily and rapidly fall to zero is called the **time base**. From this description it should be clear that the cathode ray oscillograph provides an instrument in which the mass of the moving parts is practically zero and thus it is possible to deal with very high frequencies. It is this advantage which adapts the instrument to use in the field of television.

EXERCISES ON CHAPTER IX

1. Describe two forms of galvanometer, and explain clearly how the control of the needle is effected in each case.

2. Why is a tangent galvanometer reading not proportional to the current passing? To what is the current proportional?

3. How can a suspended coil galvanometer be converted to an ammeter. Explain carefully the lines on which the scale would have to be graduated in order that this may be possible.

4. A tangent galvanometer constant is 2·5 and a current of 1 ampere produces a deflection of 45°. Mark out on a 3-inch diameter circle the graduations for this galvanometer to act as an ammeter and mark the readings 0·75, 0·5 and 0·25 ampere.

5. Why is a moving coil instrument unsuited for the measurement of alternating current. Why are the graduations on a moving iron instrument at unequal distances ?

6. Distinguish between the essential windings of a voltmeter and an ammeter, and the method of connection in a circuit.

7. Explain the use of a shunt in order to vary the sensitiveness of a galvanometer. Calculate the ratio between the galvanometer current and the total current when a shunt of resistance $\frac{1}{99}$ of that of the galvanometer is employed.

8. Describe a hot wire ammeter, and state clearly the principle on which it operates.

9. Explain methods of adapting a moving coil galvanometer (*a*) for use as a voltmeter, (*b*) for use as an ammeter to measure currents of widely different amounts.

10. Describe some form of instrument in which the pointer consists of a beam of light focussing or casting the image of a fine hair on a scale on a screen, and suggest some type of work for which this could be used.

11. Calculate the constant of a tangent galvanometer which has 5 turns of copper wire 20 cm. in mean diameter; the earth's field is 0·18 dyne.

12. Explain the meaning of the terms *deadbeat* and *control* as applied to electrical measuring instruments.

13. Find the strength of the current in amperes flowing through the galvanometer of Question 11 if the pointer is deflected 57°.

14. Summarise the principles employed in the construction of electrical measuring instruments.

15. Distinguish between moving coil and moving iron instruments, and describe the methods of control suitable for each type.

16. A cell of e.m.f. 1·8 volts and internal resistance 0·4 ohm sends a current through a galvanometer having a constant of 0·27, and a variable resistance in series. Find the strength of the current and the value of the resistance if the deflection of the galvanometer is 20°. Resistance of galvanometer $= 3{\cdot}6$ ohms.

17. Calculate the value of the constant for a tangent galvanometer having 1 turn of copper wire 30 cm. diameter. $H = 0{\cdot}18$ line per sq. cm.

18. The constant for a tangent galvanometer is 3·241. Find the value of the current in amperes for (*a*) 40° deflection, (*b*) 25° deflection. What will be the deflection for a current of 3·5 amperes ?

19. A current of 1 ampere gives a galvanometer deflection of 20°. Find the current causing a deflection of 40°.

20. A galvanometer is wound with 20 turns of wire, the coil being 30 cm. in diameter. Find (*a*) the value of the constant for the galvanometer, (*b*) the deflection for a current of 0·20 ampere. $H = 0{\cdot}18$ dyne.

21. Why, in general, should an ammeter have a very low resistance? Describe, with sketches, some form of ammeter. (U.L.C.I.)

22. To determine the resistance of a voltmeter it was connected across two terminals kept at a constant p.d. and registered 254 volts. When connected across the same terminals in series with a resistance of 12,500 ohms it registered 129 volts. Estimate the voltmeter resistance.

23. How could the B.H.P. of a prime mover be determined by using a suitable dynamo of known efficiency, external resistance and an ammeter and voltmeter? What is the use of the external resistance, and what becomes of the energy developed by the prime mover?

24. What are the advantages and disadvantages of the hot-wire ammeter? What is a more suitable and more popular type of instrument for measuring alternating currents?

25. Explain briefly the terms used and the method of generation of an alternating current.

26. To what uses could an oscillograph be put? Describe briefly one form of oscillograph.

27. Describe briefly an instrument suitable for investigating the strength and nature of magnetic fields.

MISCELLANEOUS EXERCISES

SECTION A

The abbreviations indicated in the brackets after each question are :

(U.E.I.) for questions set for the Senior First Year National Certificate by the Union of Educational Institutions.

(U.L.C.I.) for questions set for the Preparatory and Senior First Year National Certificate by the Union of Lancashire and Cheshire Institutes.

HEAT AND HEAT ENGINES

Thermometry.

1. What do you understand by heat and temperature? Sketch a Centigrade thermometer, and explain briefly how it is graduated. (U.L.C.I.)

2. Sketch and describe an ordinary thermometer. Why is mercury a suitable liquid with which to fill a thermometer, and water not a suitable liquid? (U.L.C.I.)

3. A faulty mercurial thermometer has a scale of equal divisions attached to it. On this scale the mercury stands at 30° in melting ice and at 212° in steam from water boiling in an open vessel. What would be the temperature in degrees Centigrade when this thermometer reads 58°? (U.E.I.)

4. If a thermometer was without graduations, how would you proceed to graduate it with the Fahrenheit scale without comparison with any other thermometer?

To change 1 lb. of water at 0° C. into steam at 205·1° C. requires 672·08 Centigrade heat units. State the temperature of boiling and the number of heat units required in Fahrenheit units. (U.E.I.)

5. Describe how you would obtain, by means of experiment, a curve to enable you to convert Fahrenheit to Centigrade readings for all temperatures from freezing to boiling point of water. State the apparatus required and describe how you would perform the experiment. (U.E.I.)

6. A Fahrenheit thermometer is placed in melting ice and then in steam from water boiling in an open vessel. What would be the readings shown on the thermometer? What would be the readings if a Centigrade thermometer had been used?

An accurate Fahrenheit thermometer registers 82° F., while a Centigrade thermometer hanging beside it registers 28° C.; is this Centigrade reading correct? If not, what is the correction to be applied to the Centigrade reading? (U.E.I.)

7. The melting point of lead is 320° C.; express this temperature in degrees Fahrenheit. The latent heat of steam at atmospheric pressure is 971 B.Th.U.; what is the equivalent in Centigrade heat units? (U.E.I.)

Effects of heat.

8. A steel measuring tape is exactly 100 ft. long at a temperature of 60° F. What would be its increase in length, in inches, at a temperature of 80° F., if the coefficient of linear expansion of steel is 0·0000061 per degree Fahrenheit?

Would the true length of a line be more or less than the apparent length if measured with the above steel tape when its temperature was 40° F.? (U.E.I.)

9. Describe an experiment by which you would show that copper conducts heat better than steel. Sketch neatly the apparatus used. (U.E.I.)

10. Describe carefully how the heat is transmitted from the hot gases of a fire to the water in a kettle.

If the water were subjected to atmospheric pressure, what would be the boiling point in degrees Fahrenheit and in degrees Centigrade? What would be the effect on the boiling point if the pressure in the kettle was above atmospheric pressure? (U.E.I.)

11. In an experiment to determine the coefficient of linear expansion of copper the expansion was measured by means of a micrometer placed at one end of the copper rod.

The following figures were obtained:

Initial length of rod	20 in.
Initial temperature of rod	15° C.
Final temperature of rod	97° C.
Initial reading of micrometer	0·25 in.
Final reading of micrometer	0·278 in.

Determine the coefficient of linear expansion of copper. (U.E.I.)

12. Define coefficient of linear expansion of a solid. A copper wire is 60 yards long in winter. How much longer will it be in summer if the change in temperature is 45° C.? Coefficient of linear expansion of copper = 0·000017. Give your answer in inches. (U.L.C.I.)

13. Describe any experiment you have conducted, or have seen conducted, to show the effect of heating a solid body. Sketch neatly the apparatus used and state what you deduce from the experiment. (U.E.I.)

14. In an experiment it was found that a copper rod 20 in. long increased in length by 0·028 in. when its temperature was raised 80° C. What would be the change in length of a straight copper steam pipe 100 ft. long at 16° C. if its temperature is raised over the whole length from 16° C. to 200° C.? Assume the expansion is uniform and free. (U.E.I.)

15. What is meant by "the coefficient of linear expansion of steel is 0·0000063 per degree Fahrenheit"?

The length of the separate steel rails composing a railroad is 60 feet at a temperature of 40° F. What clearance would you leave between successive rails if their ends are to be 0·05 inch apart at 120° F.? (U.E.I.)

16. Explain what you understand by the statement "the coefficient of linear expansion of aluminium is 0·0000123 per degree Fahrenheit".

The diameter of an aluminium piston is 9·1 cm. at 60° F. What will be its diameter when the mean temperature of the piston is 285° F.? (U.E.I.)

17. (*a*) Describe, briefly, with a sketch of the apparatus used, an experiment to show that, in general, metals expand when heated.

(*b*) Give an example, from engineering practice, where allowance has to be made for the expansion of a metal on heating, or contraction on cooling.

(*c*) Calculate the increase in length of a rod 100 cm. long when its temperature is raised from 10° C. to 60° C. if the linear coefficient of expansion of the metal is 0·000012 per degree Centigrade. (U.E.I.)

18. State the common effects of heat upon a solid. In what respects are the effects different upon liquids and gases? (U.L.C.I.)

19. Define the melting point of a substance.

Describe how you would find the melting point of a substance which melts between 40° C. and 100° C.

How much heat is required to change 10 gm. of ice at 0° C. to steam at 100° C.? [Latent heat of fusion of ice = 80 cal. per gm. Latent heat of steam = 536 cal. per gm.] (U.L.C.I.)

20. What is meant by the melting point of a substance?

How would you find it in the case of wax? Explain why solder is used to mend leaky kettles. (U.L.C.I.)

21. What is the difference between *evaporation* and *boiling*?

Give two instances where *evaporation* plays an important part, explaining each case. (U.L.C.I.)

22. Explain why (*a*) soldering irons are fitted with wooden handles and (*b*) heat is applied to the bottom of a kettle containing water. Describe an experiment which would support your explanation of either (*a*) or (*b*). (U.E.I.)

23. What do you understand by the terms conduction, convection, and radiation of heat? After explaining these terms, describe how the heat is transmitted from the fire in a boiler furnace to the water in the boiler. (U.E.I.)

24. (*a*) Hot water radiators are sometimes fitted as they come from the foundry and sometimes they are covered with aluminium paint. State from a heat point of view which you consider to be best, giving reasons for your answer.

(*b*) Some substances may be classified as good, and others as bad, conductors of heat. Explain the meaning of the terms and name some material used in engineering practice which may be described as a bad conductor of heat and give its practical application. (U.E.I.)

25. Given rods of various substances, describe carefully how you would show that some are good, whilst others are bad, conductors of heat. Give two examples from engineering practice in one of which materials with good conducting qualities are needed whilst the other calls for materials with poor conducting qualities. (U.E.I.)

26. From each square foot of outer surface of a bare steam pipe 3 units of heat are lost per hour for each degree difference in temperature between the pipe and the surrounding atmosphere. A steam pipe carrying steam at 300° F. is uncovered where it passes between two shops 10 ft. apart. The temperature of the air in the passage-way is 80° F. and the pipe is 4 in. external diameter. How many units of heat are lost per hour due to this exposed portion of the pipe? (U.E.I.)

27. It is proposed to heat a workshop by means of hot water pipes placed:

(*a*) close to the floor;

(*b*) at some distance above the heads of the employees.

Explain in each case how the temperature in the workshop is raised. Which do you consider, from a heating point of view, is the best arrangement, and why? (U.E.I.)

28. Explain carefully what you understand by the term "Unit of Heat". 4 lb. of water at a temperature of 95° C. are mixed with 3 lb. of water at a temperature of 12° C. Assuming that no heat has been lost during the process, what would be the final temperature of the mixture? (U.E.I.)

29. Explain carefully what you understand by the statement "the specific heat of brass is 0·09".

Describe, with neat sketches of the apparatus used, how you would determine by experiment the specific heat of a given piece of brass.

A number of brass condenser tubes, together weighing 120 lb., were at a temperature of 60° F. before the condenser was at work. When in use the mean temperature of the tubes was 108° F. How much heat was absorbed by the tubes? (U.E.I.)

30. What is meant by the "specific heat" of a substance?

Find the specific heat of brass from the following experiment. When 90 gm. of brass at 100° C. are placed in a vessel containing 40 gm. of water at 10° C., the resulting temperature is 26° C. (U.L.C.I.)

31. (a) Write down the freezing and boiling points of water at standard pressure on the Fahrenheit and Centigrade scales respectively. What is the ratio of one Fahrenheit degree to one Centigrade degree of temperature?

(b) How many units of heat are required to raise the temperature of 10 lb. of water from 60° F. to 180° F.? How many heat units would this correspond to on the Centigrade scale? (U.E.I.)

32. What is the specific heat of a substance? If 100 gm. of water at 100° C. are poured into 120 gm. of turpentine at 9° C. and the resulting temperature found to be 70° C., what is the specific heat of the turpentine? What reason have you for supposing that the result you give may not be correct? (U.L.C.I.)

33. How much heat is required to raise the temperature of 0·2 lb. of copper through 1050° C.? Assume the specific heat of copper to be 0·1.

If this heated copper is plunged into 2·2 lb. of water at 15° C., what will be the final temperature of the water, assuming no losses by radiation? (U.E.I.)

34. (a) What is the cost of heating 10 gallons of water from 52° F. to 192° F. by coal gas if the cost of the gas is 8·5 pence per therm?

(b) What would be the resulting temperature if the 10 gallons of water at 192° F. were mixed with 15 gallons of water at 52° F.?

(NOTE.—One gallon of water weighs 10 lb. and a therm equals 100,000 B.Th.U.) (U.E.I.)

35. The temperature of a furnace may be obtained by placing an iron ball in the furnace until it has reached the temperature of the furnace, then plunging it into a known weight of water and noting the rise in temperature of the water.

Calculate the temperature of a furnace from the following data:

Weight of iron ball	0·5 lb.
Weight of water	2·0 lb.
Specific heat of iron	0·114
Initial temperature of water	50° F.
Final temperature of water	90° F.

Neglect the heat given to the vessel containing the water. (U.E.I.)

36. In an experiment to determine the temperature of the exhaust gases from an internal combustion engine, 0·2 lb. of copper, of specific heat 0·1, was placed in the exhaust pipe until it attained the same temperature as the exhaust gases. This heated copper was then quickly removed and plunged into 0·8 lb. of water at 59° F. It was found that the final temperature of the water and copper was 70° F. Assuming no losses by radiation, determine the temperature of the exhaust gases. (U.E.I.)

37. In a certain cooling apparatus cold water enters the cooling tank at the bottom and leaves by an outlet near the top of the tank. The hot liquid passes through a coil entering near the top and leaving at the bottom of the tank. 3,000 lb. of liquid, of specific heat 0·42, enter the cooler per hour, the liquid entering at a temperature of 165° C. and leaving at 15° C. How much heat is liberated per hour? The cooling water enters at 12° C. and leaves at 62° C. Calculate the quantity of water, in gallons per hour, passing through the cooling apparatus.

1 gallon of water weighs 10 lb. (U.E.I.)

38. Define a pound Centigrade heat unit and a British Thermal Unit. What is the ratio of one British Thermal Unit to one Centigrade heat unit? How many pound Centigrade units of heat would be required to change the temperature of 12 lb. of lead from 15° C. to 300° C.? How many lb. of water would be raised in temperature 26° F. by this amount of heat? Specific heat of lead is 0·035. (U.E.I.)

39. What do you understand by the *latent heat of steam*?

How would you find a value for it by experiment? (U.L.C.I.)

40. Define "latent heat of ice", and find its value if it requires 50 gm. of boiling water to melt 62·5 gm. of ice at 0° C. (U.L.C.I.)

Properties of the working substance. Gas laws.

41. Describe some form of apparatus used for measuring the pressure of the atmosphere.

Would it be useful for measuring the pressure in a steam engine boiler? Give reasons for your answer. (U.L.C.I.)

42. A balloon is filled with 52,000 cubic feet of gas at sea level where the air pressure is 30 in. of mercury. At a height of 3,600 feet the air pressure is only 26 in. of mercury. What volume of gas must be released at this height to allow for the expansion of the gas?

Assume that the temperature of the air remains constant.

State the law used in your calculation. (U.E.I.)

43. (*a*) Steam is admitted to the cylinder of an engine at 60 lb. per square inch absolute, and is cut off at $\frac{1}{3}$ of the stroke. What will be the pressure on the piston when it has travelled 1 ft. 6 in., 2 ft., and at the end of the stroke if the length of the stroke is 3 ft.?

(*b*) Plot a graph showing the fall in pressure from the point of cut-off to the end of the stroke. (U.E.I.)

44. A gas is subjected to a pressure of 20 lb. per square inch absolute and occupies a volume of 5 cu. ft. What would be the volume of the gas when the pressure is increased to 95 lb. per square inch absolute, the temperature remaining constant?

Describe carefully how you would verify by experiment the law used in your calculation. Make a neat sketch of the apparatus you would use. (U.E.I.)

45. 10 cubic feet of gas at a pressure of 20 lb. per square inch absolute is compressed to a volume of 2 cubic feet, the compression taking place very slowly. Determine the pressure of the gas at the end of compression, also the volume of the gas when the pressure is 50 lb. per square inch absolute. State clearly the law used in your calculation. (U.E.I.)

46. If atmospheric pressure is 15 lb. per sq. in., what is the absolute pressure when the gauge pressure is 120 lb. per sq. in., and what is the gauge pressure when the absolute pressure is 35 lb. per sq. in.?

A machine for compressing air takes in 4 cubic feet of air at a pressure of 35 lb. per square inch absolute, and compresses it to a pressure of 120 lb. per square inch gauge. Assuming the compression takes place at constant temperature, find the final volume of the air. (U.E.I.)

47. State clearly the relation between the volume and the pressure in the case of a gas subjected to changes of pressure at constant temperature. 20 cubic feet of gas at a pressure of 115 lb. per square inch absolute are contained in a cylinder. The gas is allowed to expand, the temperature remaining constant, until the volume is 46 cubic feet. What is the pressure at the end of expansion in lb. per square inch absolute and in lb. per square inch gauge?

You may assume atmospheric pressure equals 15 lb. per square inch. (U.E.I.)

48. Explain carefully what you understand by *Charles' law*.

A gasometer holds 1,000,000 cu. ft. of gas when the temperature of the day is 30° C. What will this volume become when the temperature falls to 20 degrees below freezing point? Assume that the barometer is at the same height in both cases. (U.L.C.I.)

49. What is meant by absolute zero temperature?

The volume of a gas is 200 c.c. at 25° C. What will the volume be if it is heated to 100° C., the pressure being kept the same? (U.L.C.I.)

50. (*a*) Coal gas leaves a gas works at a temperature of 30° C. and reaches the consumer at 15° C. What is the change in volume per 1,000 cubic feet of gas leaving the gas works because of this fall in temperature, pressure remaining constant?

(*b*) How many pounds of steam at atmospheric pressure must be added to 1,000 pounds of water to raise the temperature of the water from 50° C. to 80° C., the latent heat of steam at atmospheric pressure being 540 C.H.U. and its sensible heat 100 C.H.U.? (U.E.I.)

51. In a gas engine trial it is found that 450 cubic feet of gas are used per hour at a pressure of 4 in. of water. What would be the gas consumption at atmospheric pressure, *i.e.* at 15 lb. per sq. in. absolute, without variation of temperature? You may assume that atmospheric pressure will support a column of water 34 ft. high.

If this gas consumption at atmospheric pressure was at a temperature of 18° C., what would be the gas consumption at atmospheric pressure and at a temperature of 0° C.? (U.E.I.)

52. Explain carefully how you would experimentally prove the truth of Boyle's Law *or* Charles' Law. A sketch, and description, of the apparatus used is required. (U.E.I.)

53. What do you understand by absolute pressure and absolute temperature? 1·5 cubic feet of gas at a pressure of 15 lb. per square inch absolute are contained in a cylinder. The gas is compressed at constant temperature until its pressure is 90 lb. per square inch absolute. What is then the volume of the gas?

If after compression the temperature of the gas was raised from 20° C. to 60° C., the pressure being kept constant, what would then be the volume of the gas? (U.E.I.)

54. In a gas engine trial 360 cubic feet of gas were used per hour. A manometer showed that the pressure of the gas in the mains was 0·18 lb. per square inch gauge. What would be the gas consumption at atmospheric pressure, *i.e.* at 15 lb. per square inch absolute, without variation of temperature?

If this gas consumption at atmospheric pressure was at a temperature of 65° F., what would be the gas consumption at atmospheric pressure and at 32° F.? (U.E.I.)

55. Four cubic feet of gas are compressed at a constant temperature from 20 lb. per square inch absolute to 100 lb. per square inch absolute. Find:

(*a*) The volume of the gas at the end of compression.

(*b*) The volume of the gas when the pressure was 60 lb. per square inch absolute.

(*c*) The pressure of the gas, in lb. per square inch gauge pressure, when the volume is 1·5 cubic feet. (Assume atmospheric pressure = 15 lb. per square inch absolute.)

Would the results be affected, if during the compression the temperature of the gas were allowed to vary? Give a reason for your answer. (U.E.I.)

Properties of working substances. Steam quantities.

56. How many heat units are required to generate 1,000 lb. of dry saturated steam at an absolute pressure of 175 lb. per sq. in. from feed water at 12° C.? What would be the total heat of 1 lb. of steam at the above pressure?

The following data are abstracted from a steam table.

Pressure in lb. per sq. in. abs.	Temperature, ° C.	Sensible heat, C.H.U. per lb.	Latent heat, C.H.U. per lb.
175	188·2	190·9	477·3

(U.L.C.I.)

57. The length and breadth of the fire grate of a boiler furnace are 6 ft. and 3 ft. respectively, and 14 lb. of coal are burnt per square foot

of grate area per hour. If the heat given out by the burning of 1 lb. of coal is 14,000 B.Th.U. and 87 per cent. of the heat is utilised in generating steam, how many pounds of dry steam will be produced per hour at a pressure of 120 lb. per square inch absolute from feed water supplied at a temperature of 101·8° F.?

Pressure, lb./sq. in. absolute	Temperature, ° F.	Sensible heat, B.Th.U. per lb.	Latent heat, B.Th.U. per lb.
—	101·8	69·7	1033·7
120	341·2	312·3	880·0

(U.E.I.)

58. Using the extract from the Steam Tables given, determine:

(*a*) The greatest amount of heat which can be supplied to 1·5 lb. of water at a pressure of 120 lb. per square inch absolute without the formation of any steam if the initial temperature is 75·9° C.

(*b*) The amount of heat to be supplied to 2·25 lb. of water at 181·3° C. to convert it into dry saturated steam at 150 lb. per square inch absolute.

(*c*) How many pounds of water will be evaporated by a supply of heat of 6,620 C.H.U. if the feed temperature in a boiler working at a pressure of 150 lb. per square inch absolute is 75·9° C.?

Pressure, lb. per sq. in. absolute	Temperature, ° C.	Sensible heat, C.H.U. per lb.	Latent heat, C.H.U. per lb.	Total heat of evaporation, C.H.U. per lb.
—	75·9	75·79	—	—
120	171·75	—	490·40	663·92
150	181·3	183·59	—	666·49

(U.E.I.)

59. 1200 lb. of steam are exhausted into a condenser per hour at a pressure of 5 lb. per square inch absolute. The condensed steam leaves the condenser at a temperature of 60·8° C. What heat loss, in C.H.U. per hour, does this represent?

Pressure, lb. per sq. in. absolute	Temperature, ° C.	Sensible heat, C.H.U. per lb.	Latent heat, C.H.U. per lb.
5	72·4	72·26	555·38
—	60·8	60·70	561·83

(U.E.I.)

60. The following figures have been taken from steam tables. Complete the table, and then find the amount of heat required to completely convert 5 lb. of water at 26·4° C. into steam at a pressure of 115 lb. per sq. in. absolute?

Pressure, lb. per sq. in. absolute	Temperature, ° C.	Heat of the liquid, C.H.U. per lb.	Heat of evaporation, C.H.U. per lb.	Total heat of evaporation, C.H.U. per lb.
0·5	26·4	—	580·4	606·7
50	138·3	138·3	515·3	—
115	170	171·7	—	763·4

(U.E.I.)

61. Explain the meaning of the following quantities found in steam tables: Heat of the liquid, or sensible heat; Heat of evaporation or latent heat; Total heat of evaporation.

If the heat of the liquid is 283·8 B.Th.U. per lb. and the total heat of evaporation is 1182·8 B.Th.U. per lb., what is the heat of evaporation in B.Th.U. per lb.?

If the initial temperature of the water is constant, does the heat of the liquid (as quoted in steam tables) increase or decrease as the pressure to which the water is subjected increases? Give a reason for your answer. (U.E.I.)

Conversion of energy.

62. In a run of 60 miles a locomotive used $\frac{1}{2}$ ton of coal, each lb. of which generates 14,000 B.Th.U. of heat. The average pulling force exerted by the engine was 2,000 lb.

What is the thermal efficiency?

NOTE.—Thermal efficiency $= \dfrac{\text{Heat converted into work}}{\text{Heat supplied in the same period}}$.

(Joule's Equivalent of Heat, 1 B.Th.U. = 778 ft. lb.) (U.E.I.)

63. Water is being heated by means of a paraffin burner and 5·3 lb. of the fuel are used per hour. If 1 lb. of paraffin gives out 21,000 B.Th.U. on complete burning and 75 per cent. of the heat passes into the water, raising its temperature from 60° F. to 210° F., how many pounds of water are being heated per hour? (U.E.I.)

64. An oil engine uses 20 lb. of oil per hour. If the heat liberated by the complete burning of 1 lb. of oil is 21,000 B.Th.U., how much heat is supplied per hour?

If the brake horse power of the engine is 18, what percentage of the heat supplied is converted into useful work?

778 foot pounds of work must be done to raise the temperature of 1 pound of water 1° Fahrenheit. (U.E.I.)

65. 778 ft. pounds of work are required to raise the temperature of 1 pound of water 1° Fahrenheit; find the number of foot-pounds of work required to raise the temperature of 1 pound of water 1° Centigrade. How much work would it be necessary to convert into heat in order to provide sufficient heat to raise the temperature of 12 pounds of water through 50° C.? (U.E.I.)

66. An oil engine uses 19·5 lb. of oil per hour, each pound of oil when completely burnt liberating 20,000 B.Th.U. How much heat is supplied per hour? If the brake horse power of the engine is 50, what percentage of the available heat is converted into mechanical work?

In order to raise the temperature of 1 lb. of water 1° F. 778 ft. lb. of work must be done. (U.E.I.)

67. What do you understand by *the mechanical equivalent of heat*? How much heat is required to raise the temperature of 600 lb. of water from 15° C. to 70° C.? What is the mechanical equivalent of this amount of heat? If it takes an hour to raise the temperature of the 600 lb. of water, at what rate measured in horse power is the energy supplied to the water? (U.L.C.I.)

68. To-day gas is measured for sale purposes by the *therm* (100,000 B.Th.U.). What will it cost to boil 3 lb. of water on a gas ring if the temperature of the water at the commencement is 42° F. and the charge is 1s. 8d. per therm? (Give your answer correct to the first decimal place of a penny.) (U.L.C.I.)

69. Explain as fully as possible the principle of action of an internal combustion engine working on:

(*a*) The four-stroke cycle; *or*

(*b*) The two-stroke cycle. (U.E.I.)

70. Explain carefully the cycle of operations in:

(*a*) A steam engine, *and*

(*b*) An internal combustion engine working on the four-stroke cycle. (U.E.I.)

71. Which of the following would you call internal combustion engines: gas engine, steam engine, petrol engine, heavy oil engine, paraffin engine, steam turbine? In the case of one of the engines you have selected, describe how the explosive mixture is obtained and how ignition is effected. (U.E.I.)

72. An internal combustion engine is said to work on the "four-stroke", or "two-stroke" cycle. Explain what is meant by these terms.

Describe carefully the four-stroke cycle of operations, and show by means of diagrams the positions of valves and crank at important points of the cycle. (U.E.I.)

73. The diameter of the cylinder of a double-acting steam engine is 9 in., and the length of the piston stroke is 15 in. Find what mean effective pressure of the steam would develop 15 horse-power at a speed of 125 revolutions per minute. (U.L.C.I.)

74. The cylinder of an engine is 7 in. in diameter and the piston stroke is 11 in. The mean effective pressure of the steam in the cylinder is 40 lb. per sq. in. Find the speed of the engine in revolutions per minute in order that it may develop 16 I.H.P. (U.L.C.I.)

75. A gas engine working on the four-stroke cycle has a cylinder 8 inches in diameter and a stroke of 15 inches. The mean effective pressure in the engine cylinder is 90 lb. per square inch. The crank shaft makes 200 revolutions per minute and there are 10 miss-fires per minute. Calculate :

(*a*) The total effective force on the engine piston.

(*b*) The work done during the working stroke.

(*c*) The indicated horse-power of the engine. (U.E.I.)

76. Explain the "four-stroke cycle" for an internal combustion engine.

An internal combustion engine working on the four-stroke cycle has an explosion every cycle. The cylinder diameter is 8 in. and the piston stroke is 11 in. Find the I.H.P. of the engine when the mean effective pressure during the working stroke is 55 lb. per sq. in. and the speed is 220 revolutions per minute. (U.L.C.I.)

77. An engine uses 175 cubic feet of gas per hour. If 340 C.H.U. are liberated by the complete burning of 1 cubic foot of gas, how much heat is supplied per hour? If the brake horse power of the engine is 6·3, what percentage of the heat supplied is converted into useful work? If 280 lb. of water pass through the jackets per hour and the rise of temperature of the jacket water is 60° C., what percentage of the heat supplied is carried away by the jacket water?

1400 foot-pounds of work are equivalent to 1 C.H.U. (U.E.I.)

78. The following figures were obtained during a test of an oil engine :

Diameter of brake drum	1·5 feet.
Effective load on brake	65 lb.
Revolutions per minute	620
Oil consumed per hour	3·9 lb.
Heat evolved on the complete combustion of 1 lb. of oil	18,000 B.Th.U.

Find :

(*a*) the brake horse-power of the engine ;

(*b*) the heat supplied per minute.

(*c*) the percentage of the heat supplied converted into useful work.

778 foot-pounds of work are equivalent to 1 B.Th.U. (U.E.I.)

79. A plant used for experimental purposes consists of boiler, turbine and generator. In a test it was found that 20 lb. of oil were burnt per hour, each pound of oil, on complete burning, giving out 18,000 B.Th.U. 22 amperes of current were generated at a pressure of 480 volts. Find the overall efficiency of the plant.

778 ft. pounds are equivalent to 1 B.Th.U. (U.E.I.)

80. Steam at an absolute pressure of 80 lb. per sq. in. is admitted to the cylinder of an engine and is cut off at 0·4 stroke, the back pressure being 17 lb. per sq. in. Draw, to scale, the hypothetical indicator diagram (in which expansion follows the law pv = constant), and determine the mean effective pressure of the steam during the stroke. (U.L.C.I.)

ELECTROTECHNICS

Chemical effect of a current and generation by chemical means.

1. State the laws of electrolysis.

Describe, as fully as you can, what occurs when an electric current is passed through a solution of copper sulphate. (U.L.C.I.)

2. (1) Describe the action of a current of electricity when passing through (*a*) copper sulphate solution, (*b*) a solution containing nickel, (*c*) water containing a small amount of sulphuric acid.

(2) Briefly explain silver-plating. (U.L.C.I.)

3. State Faraday's laws of electrolysis.

Describe an experiment by which the electro-chemical equivalent of copper may be found. Give a connection diagram. (U.E.I.)

4. What is understood by the electro-chemical equivalent of an element?

The weight of copper deposited in a copper voltameter is 1·64 gm. in 8 min. 20 sec. Calculate :

(*a*) The quantity of electricity passed through the voltameter.
(*b*) The average value of the current.

(Electro-chemical equivalent of copper = 0·000328.) (U.E.I.)

5. In an experiment to determine the electro-chemical equivalent of copper, the following results were obtained.

Initial weight of plate, 29·82 gm.
Final weight of plate, 30·48 gm.
Current, 2 amp.
Time, 16 min. 40 sec.

Calculate the experimental value of the electro-chemical equivalent of copper.

What precautions should be taken in carrying out this experiment? (U.E.I.)

6. Define the electro-chemical equivalent of an element. A metal plate having a surface of 200 sq. cm. is to be silver-plated. If a current

of 0·5 ampere is used for a period of one hour, what thickness of silver will be deposited on the plate given that the E.C.E. of silver is 0·001118 and its density is 10·6 grams per c.c. (U.E.I.)

7. What happens when a plate of zinc and a plate of copper are dipped into dilute sulphuric acid, and connected externally by a copper wire? What are the defects of this simple cell?

Describe one form of cell in which these defects are overcome. (U.L.C.I.)

8. What are the defects of a simple cell? What methods are adopted to overcome them in any primary cell with which you are familiar? Describe the construction and action of the primary cell, and state what you consider to be its advantages and disadvantages. (U.L.C.I.)

9. Make a sketch of a Leclanche cell, naming the various parts and substances used.

What is the cause of polarisation, and how is it reduced in this type of cell? (U.E.I.)

10. In what way is the electro-motive force and the current in a circuit related? An electric lamp having an electro-motive force of 230 volts between its terminals takes a current of 0·46 ampere. Calculate the resistance of the lamp. If the electro-motive force changes to 200 volts, what current will it now take? (U.L.C.I.)

11. Express Ohm's law in words.

If a battery of 6 cells, each 1·4 volts e.m.f. and 0·5 resistance, are connected in series with a galvanometer of 25 ohms resistance and a wire of 100 ohms resistance, what current will flow in the circuit? (U.L.C.I.)

12. What is meant by (*a*) the e.m.f., (*b*) the p.d. of a primary cell?

Four primary cells each having an internal resistance of 1·8 ohms are connected in series and send a current through two conductors joined in parallel, the resistance of the conductors being 8 and 12 ohms respectively. The current through the conductor of 8 ohms resistance is found to be 0·3 ampere. Determine the drop of voltage in each cell. (U.L.C.I.)

13. Define (*a*) Ampere; (*b*) Volt; (*c*) Ohm.

Two cells, each having an e.m.f. of 1·5 volts and an internal resistance of 1·2 ohms, are connected in series. A resistance of 3·6 ohms is connected across the terminals of the battery. Calculate:

(*a*) The current supplied by the battery.
(*b*) The p.d. between the terminals of the battery.
(*c*) The power expended in the 3·6 ohm resistance. (U.E.I.)

14. A battery consists of five cells connected in series. Each cell has an e.m.f. of 2·0 volts and an internal resistance of 0·1 ohm. The battery is connected to a resistance of 0·5 ohm. Calculate:

(*a*) The current supplied by the battery.
(*b*) The p.d. between the battery terminals.

(c) The current supplied by the battery if one of the cells be connected in the reverse direction. (U.E.I.)

15. A battery consists of four cells connected in series. Each cell has an e.m.f. of 1·5 volts and an internal resistance of 0·6 ohm. The battery is connected to a resistance of 3·6 ohms. Calculate :

(a) The current supplied by the battery.
(b) The p.d. of the battery.
(c) The value of the additional resistance required to be connected in series to reduce the current to 0·3 amp. (U.E.I.)

16. State Ohm's Law in words. Two wires, of resistance 4 and 6 ohms respectively, have their ends connected so that they are in parallel. The combination is then joined in series with another wire of 1·6 ohms resistance, and a potential difference of 12 volts is applied to the ends of the complete circuit. What is the value of the current flowing through the circuit ? (U.L.C.I.)

17. Three resistances, of 2, 3 and 6 ohms respectively, are connected in parallel, and the group thus formed joined in series with another resistance of 4 ohms. A potential difference of 20 volts is applied to the ends of the complete circuit. What is the total current through the circuit ? (U.L.C.I.)

18. Define : Ohm ; Joule ; and B.O.T. unit.

Two coils, one 6 ohms and the other 4 ohms resistance, are connected in parallel and the combination is connected in series with a third coil. The circuit thus formed is connected to a 20-volt supply and the current taken is 4 amp. Draw a connection diagram and calculate the resistance of the third coil. (U.E.I.)

19. A certain electrical circuit connected to constant voltage supply consists of two coils B and D, joined in series. Coil B has a resistance of 3 ohms, and coil D a resistance of 7 ohms. A voltmeter connected across the ends of coil B registers 7·5 volts.

Coil B is then removed from the circuit and the current again allowed to flow. Compare the quantities of electricity flowing through the circuit in the same time for the two cases. (U.L.C.I.)

20. What is meant by the terms *in series* and *in parallel* when applied to electrical circuits?

The resistance of a certain electrical instrument is 150 ohms. A wire of 30 ohms resistance is joined in parallel with the instrument. What amount of external resistance would have to be added in order that the insertion of the above shunt may not change the total resistance of the circuit?

What proportion of the total current will pass through the instrument? (U.L.C.I.)

21. Define the unit in which the difference of potential across the ends of an electrical circuit is measured. A certain uniform wire 105 cm. in length and having a resistance of 1·2 ohms connected in

series with an adjustable resistance and a single storage cell. If the internal resistance of the cell is 0·085 ohm and its e.m.f. is 2 volts, what must be the value of the adjustable resistance so that the drop along the uniform wire may be 0·01 volt per cm.? (U.L.C.I.)

22. Define: Ampere, Ohm, and Volt.

Three resistances, 4 ohms, 3 ohms, and 12 ohms are connected in parallel. This combination is connected in series with a resistance of 8·5 ohms and the circuit thus formed is connected to a 100 V. supply. Give a connection diagram and calculate the current taken from the supply. (U.E.I.)

23. Define: (*a*) Watt; (*b*) Joule; B.O.T. unit.

A 250-volt electric light installation consists of the following: six lamps each 100 watts, five lamps each 60 watts, and ten lamps each 30 watts, all connected in parallel. If all the lamps are switched on, calculate: (*a*) the current taken from the supply; (*b*) the cost of lighting for 10 hours if the price of electricity is 2d. per B.O.T. unit. (U.E.I.)

24. What resistance must be connected in series with a 60-watt, 110-volt lamp in order that it may run on 230-volt mains? If the cost of electrical energy is 2d. per unit, calculate the cost of running per hour. (U.E.I.)

25. How does the resistance of an electrical conductor vary with its length, and with its cross-sectional area?

1,000 yards of 22-S.W.G. copper wire has a resistance of 39 ohms, the cross-sectional area of the wire being 0·000616 sq. in. Deduce from this the specific resistance or resistivity of copper. (U.L.C.I.)

26. A two-core cable one mile in length has a total resistance of 1·25 ohms. If the conductor diameter is 0·3 in., calculate the specific resistance of the conductor material in inch measure. What is the power loss in the cable when it is carrying a current of 30 amperes? (U.E.I.)

27. An aluminium wire 10 metres long and 2 mm. diameter is joined in parallel with a copper wire 6 metres long. The total current flowing through the combination is 2 amperes, and in the aluminium wire 1·25 amperes. Find the diameter of the copper wire.

Specific resistance of copper = 1·6 microhms per cm. cube.
Specific resistance of aluminium = 2·6 microhms per cm. cube. (U.L.C.I.)

28. It is required to make a 10-ohm resistance coil using manganin wire of 0·0009 sq. cm. sectional area. Given that the specific resistance of manganin is 45 microhms per cm. cube, calculate the length of wire required.

If this coil be connected in parallel with another of 15 ohms resistance, calculate the combined resistance of the two coils. (U.E.I.)

29. A circular field coil is connected to a 100-volt supply and the current is 0·8 amp. Calculate:

(a) The length of wire used if the diameter of the bare copper is 0·020 in.

(b) The number of turns if the mean diameter of the coil is 6 in.

(Take specific resistance of copper as 0·67 microhms per inch cube.) (U.E.I.)

Heating effect of a current.

30. State clearly the law relating to the conversion of electrical energy into heat. How would you prove the law experimentally? A galvanometer of 500 ohms resistance is shunted by a 50 ohms coil. Compare the amounts of heat generated in the galvanometer and its shunt when connected up in a circuit. (U.L.C.I.)

31. The power taken by a certain electric saucepan when used on a 220 volt circuit is 300 watts. Determine (a) the resistance of the heating element of the saucepan, (b) the electrical energy taken by the saucepan in 5 minutes, (c) the amount of water which could be heated in the saucepan from 15° C. to boiling point in the time stated, if the whole of the electrical energy was used to heat the water. (U.L.C.I.)

32. An electric kettle contains 2 pints of water, and it is required to raise the temperature of the water from 20° C. to 100° C. in 10 min. If 80 per cent. of the heat which is produced in the heating element is usefully employed in heating the water, calculate the resistance of the element, the supply pressure being 200 volts (1 lb. = 450 grams). (U.L.C.I.)

33. A coil consists of 50 metres of 0·02 cm. diameter copper wire. Calculate (a) the resistance of the coil, and (b) the power taken by the coil when connected to a 100 V. supply.

(Take specific resistance of copper as 1·7 microhms per cm. cube.) (U.E.I.)

Magnetism and electromagnetism.

34. What are the poles of a magnet?

(b) How would you show that a magnet has two poles which are opposite in character? (U.L.C.I.)

35. What do you understand by the terms "permanent magnet" and "poles of a magnet"? Give the properties which a material should possess for the purpose of being made into a permanent magnet. (U.L.C.I.)

36. Draw, as carefully as you can, the field of force due to a pair of bar magnets placed in the form of a T.

37. Sketch the distribution of the magnetic field due to a horse-shoe magnet: (a) without keeper; (b) with a keeper placed so that there is a small gap between the keeper and each pole; (c) fitted with pole

pieces and a soft iron cylinder between the poles as in a moving coil instrument. In each case show the polarity of the magnet and the direction of the magnetic field. (U.E.I.)

38. When two north seeking poles are placed near together they repel each other. How does the force of repulsion between the two poles vary with their distance apart? Explain in detail how you would proceed to prove the truth of your statement by experiment. (U.L.C.I.)

39. Define unit magnetic pole.

State the law of inverse squares as applied to magnetic poles and describe an experiment which demonstrates this law. (U.E.I.)

40. Describe the magnetometer and explain how you would use the instrument to compare the strength of two bar magnets. (U.E.I.)

41. In what terms is the strength of the magnetic field at any place expressed?

Determine the strength of the magnetic field due to a thin bar magnet 6 cm. long and 50 units pole strength at a point 4 cm. from the north-seeking pole on the axis of the magnet produced. (U.L.C.I.)

42. Calculate the force exerted on a unit pole by a bar magnet 12 cm. long and of pole strength 25 units, the unit pole being situated at a perpendicular of 5 cm. from the N. seeking pole of the magnet. Solve graphically or otherwise. (U.L.C.I.)

43. Define unit magnetic pole.

Two magnetic poles of strengths 10 and 12 units respectively are placed 4 cm. apart. How far apart must two poles of strengths 28 and 45 units respectively be placed, in order that the force between them shall be 3·5 times as great as that between the previous poles? (U.L.C.I.)

44. Describe in detail two different methods of magnetising a piece of iron. Illustrate your answer by sketches, indicating clearly the N. pole of the iron. How would you prove the iron had been magnetised? (U.L.C.I.)

45. What properties would you expect any permanent magnet to possess? Is it possible to obtain a magnet which when freely suspended so as to swing horizontally will set with its length at right angles to the magnetic meridian? If so, sketch and explain in detail the methods of magnetisation which could be used for obtaining such a magnet. (U.L.C.I.)

46. How can you show by experiment: (*a*) that magnetism may be induced, and (*b*) the polarity of the induced magnet? Give a sketch showing the inducing and induced magnets in position, and mark the N. and S. poles on each. (U.L.C.I.)

47. Define unit magnetic pole.

A soft iron ring is placed between, but not touching, the North pole of one bar magnet and the South pole of another. Sketch the distribution of the magnetic field between the poles. Show by means of arrows the direction of the field and account for the general shape. (U.E.I.)

48. A magnet of length 10 cm. is suspended in a magnetic field of which $H=0{\cdot}18$. If the strength of each pole is ten units, find the moment of the couple required to deflect the magnet (1) through 30°, (2) through 90°. (U.E.I.)

49. How would you show that there is a magnetic field at the centre of a coil of wire through which a current is passing? Show how you can determine the direction of the current by testing the magnetic action of the field. (U.L.C.I.)

50. Explain the action of a simple induction coil. (U.L.C.I.)

51. What is an electro-magnet and on what factors does the strength of such a magnet depend? What do you imagine takes place when an electric current is allowed to flow through a coil of insulated wire wound round a piece of soft iron? State the functions of the electro-magnet in any three practical cases where you know such a magnet is usefully employed. (U.L.C.I.)

52. What are the properties of a magnet? How can a piece of steel be made into a magnet (*a*) by means of other magnets, (*b*) by means of an electric current? Give neat sketches to illustrate the methods you use, showing clearly in the sketches the polarity of the steel. (U.L.C.I.)

53. You are given a straight length of conductor carrying a strong electric current and a suitable switch for starting and stopping the current when required. What additional apparatus would you need and how would you proceed to use it in order to show that an electric current produces a magnetic field in its neighbourhood? Sketch the direction of the lines of force for such a case, and explain how you would use the results of your experiments in order to determine the direction of the current flowing through the conductor. (U.L.C.I.)

54. A wooden cylinder of length 24 cm. and cross-sectional area 2 sq. cm. is uniformly wound with 120 turns of insulated copper wire. An electric current of 5 amperes is passed through the coil thus formed. Calculate the total magnetic flux within the coil. If the wooden cylinder were removed and an iron cylinder of identical dimensions substituted, how would the flux density be affected? (U.L.C.I.)

55. Why does a bar of steel become magnetised when it is wound along its length with turns of insulated wire carrying an electric current? State any rule which could be used for determining the polarity of the steel.

If the steel was in the form of a ring, explain how it could be magnetised to have (*a*) no poles at all evident, (*b*) a north seeking pole at one point on the ring and a south seeking pole diametrically opposite. Illustrate your answer by sketches. (U.L.C.I.)

56. Define ampere.

What are the effects of an electric current? Describe an experiment to illustrate each effect. (U.E.I.)

57. How do you define induced e.m.f. and what do you understand by the right hand rule? A conductor of length 25 cm. is moving with a velocity of ten metres per second at right angles to the lines of force of a magnetic field. If the induced e.m.f. is 1·0 volt, calculate the strength of the field. (U.E.I.)

58. State Lenz's law of electromagnetic induction.

Describe an experiment illustrating this law. (U.E.I.)

Generators and motors.

59. How could you, by simple experiments with a bar magnet, induce an electric current in a coil of wire?

State briefly how this is utilised in a dynamo. (U.L.C.I.)

60. Describe the principle of action of a generator. Upon what factors do the value and direction of the e.m.f. depend? (U.E.I.)

61. Describe with the aid of sketches, and indicate the function of, the essential parts of a direct current machine. (U.E.I.)

62. Describe an experiment illustrating the principle of action of the generator.

Explain why the p.d. between the terminals of a shunt generator falls as the load is increased. (U.E.I.)

63. In a certain building the electrical equipment is as follows: twenty 100 watt lamps, fifty 60 watt lamps, one hundred 40 watt lamps, four 2 kW. heaters. The heating load averages 5 hours per day, and the lighting load 2 hours per day for a six-day week. What is the energy expended per week in kW. hours? If the building is supplied by a single dynamo of 85% efficiency, what must be the H.P. of the engine driving the dynamo? (U.L.C.I.)

64. Define: Joule, Watt and kW.-hour.

A 200-volt generator supplies twenty 100 watt and fifty 60 watt lamps all connected in parallel. The efficiency of the generator when supplying this load is 85 per cent. Calculate:

(*a*) The total current supplied to the lamps.

(*b*) The H.P. required to drive the generator (neglecting loss in cables). (U.E.I.)

65. Describe briefly the action of a simple electric motor. (U.L.C.I.)

66. Under certain conditions a conductor situated in a magnetic field will experience a mechanical force. What are these conditions and upon what factors does the direction of the force depend?

Give sketches of the essential parts of a D.C. motor and name them. (U.E.I.)

Instruments.

67. Sketch and describe some form of galvanometer, and explain clearly its use and the principles upon which it acts. (U.L.C.I.)

68. With the aid of a suitable sketch describe the construction and action of a hot wire ammeter, and state what you consider to be the

defects of this instrument. Why is the drop in volts across such an instrument large, compared with that across the moving coil type, and what device is used in some hot wire ammeters to reduce this drop? (U.L.C.I.)

69. Explain the principle of action of a moving coil ammeter. Make a large diagrammatic sketch showing the principal parts of a moving coil ammeter, and explain the details of its construction. What is the function of the shunt used with such an instrument? (U.L.C.I.)

70. Describe the construction, and principle of action, of a moving coil instrument. Give sketches. (U.E.I.)

71. Describe, giving a sketch, the construction and principle of action of a moving coil instrument. Explain how the instrument may be used as: (*a*) a voltmeter; (*b*) an ammeter. (U.E.I.)

72. With the aid of sketches describe the construction of an ammeter shunt resistance.

A certain moving coil instrument is designed to give full deflection with a current of 25 milli-amperes and a p.d. of 75 milli-volts.

Find the values of the shunt resistance required so that the instrument may operate as (*a*) a 0 to 5 ammeter, (*b*) a 0 to 50 ammeter. (U.L.C.I.)

73. Explain the principle of the shunt. The voltage drop across a particular ammeter when reading full-scale at ten amperes is one volt. Calculate the resistance which must be connected in shunt with the instrument in order to increase its range to 100 amperes. (U.E.I.)

74. With the help of a diagram, describe the construction and principle of operation of the moving iron type of voltmeter. In what way does such an instrument differ from a moving iron ammeter? (U.E.I.)

75. A moving coil instrument has a resistance of 5 ohms, and gives a full-scale deflection with 75 milli-volts across its terminals.

A shunt resistance and a series resistance are required so that the instrument may be used (*a*) as a 0 to 5 ammeter, and (*b*) as a 0 to 100 voltmeter. Calculate the values of the shunt and series resistances necessary for this purpose. (U.L.C.I.)

SECTION B

The abbreviations indicated in the brackets after each question are :

(W.S.) for questions set for Stage I in Motive Power in the Organised Continuation Classes in the West of Scotland.

(U.L.C.I.) for questions set for the Senior Second Year National Certificate by the Union of Lancashire and Cheshire Institutes.

(U.E.I.) for questions set for the Senior Second Year National Certificate by the Union of Educational Institutions.

(I.Mech.E.) for questions set at the Studentship examination by the Institution of Mechanical Engineers.

(I.E.E.) for questions set at the Graduateship examination by the Institution of Electrical Engineers.

HEAT AND HEAT ENGINES

Effects of heat and heat quantities.

1. What is meant by the coefficient of linear expansion of a solid? Describe an accurate method of measuring this coefficient for a rod of metal such as brass. If steel rails are subjected to a range of temperature between $+8°$ F. and $120°$ F., what space must be left between rails 30 ft. long when laid at a temperature of $56°$ F.? The coefficient of linear expansion of steel is 0·0000123 per Cen. degree. (I.E.E.)

2. How would you investigate the linear expansion of a metal with rise of temperature? A fire bar 3 ft. long at $0°$ C. has a mean temperature of $900°$ C. when the fire is alight. Find its length then, assuming that the coefficient of linear expansion of its material is 0·0000118. What effect on the shape of the bar has the fact that the top of the bar is hotter than the bottom? (I.Mech.E.)

3. Describe and give diagrams of an instrument suitable for measuring a pressure of about 5 atmospheres such as exists in a high-pressure hot water heating system, and explain how you would test the instrument for accuracy. (I.Mech.E.)

4. Describe how the temperature of (*a*) the flames in the firebox, (*b*) the flue gases, of a steam boiler can be measured, giving diagrams and explaining the principles used. (I.Mech.E.)

5. 9·5 units of heat are required to raise the temperature of 5 lb. of copper $20°$ F. What is the specific heat of the copper? Would the value of the specific heat be altered if either the unit of mass or the scale of temperature is changed. Give reasons for your answer. (U.E.I.)

6. Define specific heat, and describe how you would make an experimental determination of the specific heat of a liquid. A mass of silver weighing 20 gm. was heated to $100{\cdot}2°$ C. and dropped into 69·2 gm. of turpentine at $11{\cdot}1°$ C. The water equivalent of the calorimeter was

3·1 gm., and the specific heats of silver and turpentine are respectively 0·056 and 0·42. Find the final temperature of the turpentine. (I.E.E.)

7. What is meant by (*a*) latent heat of fusion of ice, (*b*) latent heat of vaporisation of water? Describe how the specific heat of a solid may be determined by making use of either of these two quantities. (I.E.E.)

8. Explain what is meant by the method of mixtures used in calorimetry, and describe its application to the determination of the specific heat of a solid, stating the corrections necessary in accurate work. To 120 gm. of water at 18·31° C. is added wet ice weighing 10·32 gm. The final temperature is 10·72° C. Find the amount of water added with the ice, if the latent heat of fusion of ice is 80 calories per gm. (I.E.E.)

Conversion of energy, combustion and calorific value.

9. If 14,580 B.Th.U. are evolved by burning 1 lb. of coal, express this in pound Centigrade heat units, foot-pounds, horse-power per hour units and kilowatt per hour units.

A plant burning this coal has an overall efficiency of 6·8 per cent. What is the coal consumption per kilowatt per hour? (U.E.I.)

10. Explain the meaning of the term "mechanical equivalent of heat". Describe one method of determining the value of the equivalent, indicating how the result is obtained from the observations. (I.E.E.)

11. Describe an experiment to determine the mechanical equivalent of heat. A gas engine uses 450 cubic feet of gas per hour, the brake horse-power of the engine being 10. If 1 cubic foot of gas in burning gives out 531 B.Th.U. (295 C.H.U.), what is the heat efficiency of the engine? (U.E.I.)

12. What do you understand by the mechanical equivalent of heat?

An oil engine, developing 20·6 brake horse-power, uses 12·8 lb. of oil per hour of calorific value 9,000 C.H.U. per lb. What is its thermal efficiency? If 540 lb. of cooling water pass through the cylinder jacket per hour, inlet and outlet temperatures of the water being 16° C. and 72° C. respectively, what percentage of the heat supplied is carried away by the jacket water? (U.E.I.)

13. Describe a modern laboratory method of determining the mechanical equivalent of heat.

Calculate the difference in temperature between the water at the top and bottom of a waterfall 25 metres high, assuming that 15 per cent. of the energy of fall is spent in heating the water. (I.E.E.)

14. Define the mechanical equivalent of heat and state it in joules per calorie. A two-unit (kW.-hour) heater is immersed in a tank containing 20 gallons of water. How long will it take to raise the temperature

from 50° F. to 120° F.? The water equivalent of the tank and all radiation and convection losses are to be neglected. The gallon contains 10 lb. of water and 1 lb. = 453·6 grams. (I.E.E.)

15. Make an outline sketch of a calorimeter used for determining the calorific value of a sample of coal.

The following data were recorded during an experiment with a calorimeter: weight of coal burnt, 1 gram; weight of water in calorimeter, 1,020 gm.; water equivalent of calorimeter, 170 gm.; initial temperature of water, 16·2° C.; final temperature of water, 23·3° C. Determine the calorific value of 1 lb. of the sample of coal used in C.H.U. and in B.Th.U. (U.L.C.I.)

16. The percentage composition of a sample of coal is 89% carbon, 3·1% hydrogen, and 3% oxygen. Calculate the minimum weight of air required for the complete combustion of 1 lb. of this coal. If 50% of excess air is supplied, find assuming complete combustion, the weights of the respective flue gases per lb. of coal burnt. (U.L.C.I.)

17. The analysis by weight of a certain coal is carbon 82 per cent., hydrogen 5 per cent., non-combustibles 13 per cent. Determine:

(*a*) The theoretical weight of air required for the complete combustion of 1 lb. of this coal.

(*b*) The percentage composition, by weight, of the products of combustion, assuming no excess air was supplied.

Atomic weights: hydrogen 1, carbon 12, oxygen 16.

Note that there is 1 lb. of oxygen in 4·35 lb. of air. (U.E.I.)

18. Explain what is meant by "minimum air" and "excess air" when applied to combustion problems. Why is excess air usually supplied?

Calculate the minimum quantity of air necessary for the complete combustion of 1 lb. of fuel of the following composition by weight, C. 85; H_2, 14.

If this fuel is consumed in a boiler furnace with 65 per cent. excess air, and the temperature of the flue gases at the entrance to the chimney is 490° F., calculate the proportion of the total flue gas loss of heat at the chimney that is due to the excess air. Air temperature, 60° F.; specific heat of flue gases, 0·26, and of air, 0·24. (W.S.)

19. Petrol has the approximate formula C_6H_{14}. Calculate the approximate lower calorific value and the theoretical air required per lb. of petrol for complete combustion. If the excess air is 30 per cent. of the theoretical quantity required for combustion, determine the heat carried off by the exhaust gases at 820° F. per lb. of petrol used.

Take the specific heat of flue gases as 0·25 and the combustion of petrol in accordance with the equation:

$$2C_6H_{14} + 19O_2 = 12CO_2 + 14H_2O.$$

Take the calorific value of carbon as 14,550 B.Th.U. per lb. and of hydrogen as 52,250 B.Th.U. per lb.; and the composition of the air by weight as 77 per cent. nitrogen and 23 per cent. oxygen. (W.S.)

20. The oil consumed in a boiler plant has a percentage composition by weight C 86, H_2 13.

Determine its approximate calorific value. If the actual air supplied is 60 per cent. in excess of the theoretical quantity required, estimate the weight of air to be dealt with by the forced draft fan, and the weight of flue gases to be dealt with by the induced draft fan, if the oil consumption is 1,500 lb./hour.

If the free air was at 30 in. barometer and 60° F. temperature, what would be the volume dealt with by the forced draft fan.

Molecular weights—C. 12 ; O_2 32 ; H_2 2.
Composition of air by weight—O_2 23% ; N_2 77%.
Calorific values—C. 14,500 ; H_2 62,000 B.Th.U./lb.
Constant for air in gas equation—53·2. (W.S.)

Laws of permanent gases.

21. A tank of 120 cu. ft. capacity contains air at a gauge pressure of 100 lb. per sq. in. and at a temperature of 29° C. Water is then forced into the tank until the gauge pressure is 125 lb. per sq. in., and at the same time the temperature is raised to 65° C. Determine the reduction of volume of the air. (U.L.C.I.)

22. State Boyle's Law and Charles' Law, and write down the characteristic equation of a gas.

One pound weight of air at 0° C. and at an absolute pressure of 15 lb. per square inch occupies a volume of 12·4 cubic feet. What is the volume occupied by the same weight of air at 15° C. and at a pressure of 100 lb. per square inch absolute? (U.E.I.)

23. State the meaning of each letter in the equation $PV=RT$ as applied to a perfect gas.

In the measurement of the gas supplied to a gas engine it is usual to reduce the gas consumption to standard temperature and pressure, *i.e.* a temperature of 0° C. and a pressure of 14·7 lb. per square inch absolute. In an actual test the gas consumption was 40 cu. ft. per hour at a temperature of 18° C. and at a pressure of 15·2 lb. per square inch absolute. What would be the gas consumption at standard temperature and pressure? (U.E.I.)

24. Explain how you verify the laws according to which the volume of a gas varies with temperature and pressure.

The air in an excavating caisson of 48 cubic metres capacity has to be maintained at 10° C. and 34 lb. per sq. in. abs. pressure and renewed six times per hour. What volume of air outside at 0° C. and 14·7 lb. per sq. in. will have to be taken in and pumped into the caisson per hour? (I.Mech.E.)

25. A gas-propelled bus runs 100 miles per day and uses 46 cu. ft. of gas, at atmospheric pressure, per mile. The gas used for the day is carried in a gas-container under a pressure of 200 atmospheres. Calculate the capacity of the container. What would be the cost of the gas

used in a day's run if the gas were supplied at 10d. per 1000 cu. ft., and it cost $7\frac{1}{2}$d. per 1,000 cu. ft. for compression? Assume constant temperature throughout the operations. (U.L.C.I.)

26. State Boyle's law, and draw an accurate diagram of an apparatus for verifying it; explaining how the apparatus is used.

The tube of a barometer has a cross-sectional area of 1 cm.^{2}, and when the column stands at 75 cm. 2 cm.^{3} of air at atmospheric pressure are passed up the tube. How far is the surface of the mercury depressed, if initially it was 8 cm. below the closed end of the tube? The tube stands in a large vessel containing mercury, and the level of the latter is not appreciably altered when the air enters. (I.E.E.)

27. Determine the weight of air in a receiver of 150 cu. ft. capacity, the pressure of the air being 120 lb. per sq. in. abs. and the temperature 30° C. One cu. ft. of air at 0° C. and at a pressure of 14·7 lb. per sq. in. weighs 0·0807 lb. (U.L.C.I.)

28. State and explain the laws of Boyle and Charles for perfect gases. Show that these two laws may be expressed in the form of a single equation.

Compare the volumes of equal masses of air (*a*) at −20° C. and 770 mm. pressure, and (*b*) at 40° C. and 787 mm. pressure. (I.E.E.)

29. A given mass of air has a volume of 3 cu. ft. when its pressure is 200 lb. per sq. in. absolute and temperature 177° C.

(*a*) Calculate the work done and its new temperature when it expands to a volume of 9 cu. ft., its pressure of 200 lb. per sq. in. absolute remaining constant.

(*b*) What would be the work done, if any, and the new temperature if a reduction in the original temperature caused the pressure to become 20 lb. per sq. in. absolute, its volume remaining constant at 3 cub. ft. (U.E.I.)

Properties of steam and steam quantities.

30. Describe how you would verify that the latent heat of steam at atmospheric pressure is 538. Show by a diagram how its value depends on the pressure. (I.Mech.E.)

31. Heat is supplied to 1 lb. of water at 0° C. until all the water is converted into steam, the steam then being further heated, the pressure remaining constant throughout. Describe, in order, the changes that take place. Show by means of a neatly drawn graph, plotting temperature vertically and heat units supplied horizontally, the connection between temperature and heat units supplied for 1 lb. of water at 0° C. converted into steam at 100° C. and then further heated under the above conditions. You should indicate on your graph the approximate number of heat units contained by the fluid at any point where the slope of the graph changes suddenly. (U.E.I.)

32. What do you mean by the latent heat of steam and how would you measure it? In what way does it vary with the temperature at which the steam is generated? (I.Mech.E.)

33. What do you understand by the "dryness fraction" of steam?

The following is an extract from Callendar's *Steam Tables* of the properties of saturated steam:

Absolute pressure in lb. per sq. in.	Temperature (° C.)	Sensible heat (C.H.U. per lb.)	Total heat (C.H.U. per lb.)
410	231·1	237·8	677·1
420	232·5	239·3	677·3
430	233·8	240·8	677·5
440	235·1	242·3	677·8

A boiler generates steam at an absolute pressure of 425 lb. per sq. in. but the steam contains 5% of suspended moisture. Find the quantity of heat in each pound of wet steam. (U.L.C.I.)

34. What do you understand by "wet saturated" and "superheated steam"?

Find the number of heat units required to produce 1 lb. of steam at 361° F. from feed water at 120·2° F.

(*a*) when the steam contains 5 per cent. of moisture;

(*b*) when the steam is superheated to 400° F., assuming the specific heat of superheated steam to be 0·5.

Temperature, ° F.	Heat of the liquid, B.Th.U. per lb.	Total heat of evaporation, B.Th.U. per lb.
120·2	88·0	1022·9
361	332·9	1193·9

(U.E.I.)

35. What do you understand by *wet steam, dry saturated steam* and *superheated steam*? Determine the quantities of heat required to generate 1 lb. of steam at a pressure of 110 lb. per sq. in. abs. from water at a temperature of 25° C.: (*a*) when the dryness fraction is 0·88; (*b*) when it is dry and saturated; and (*c*) when it is superheated at constant pressure to 270° C., assuming the mean specific heat of the superheated steam to be 0·55. (U.L.C.I.)

36. In an experiment to determine the heat evaporation of water, steam is generated in a small boiler. The steam passes through a separator and the dried steam is then condensed in water contained

in a well-lagged calorimeter. Using such an apparatus the following figures were obtained:

Temperature of steam	110° C.
Weight of water in calorimeter	20 lb.
Initial temperature of water	15° C.
Weight of water and condensed steam	20·5 lb.
Final temperature of water	30° C.

Determine the heat of evaporation of the water.

This figure was not accepted, and the following additional data was obtained:

Weight of calorimeter	5 lb.
Specific heat of metal of calorimeter	0·10

Re-calculate the heat of evaporation of the water.

Assume that 1 C.H.U. is required to change the temperature of 1 lb. of water 1° C. throughout the temperature range. (U.E.I.)

37. Steam is supplied to the nozzle box of a turbine at 350 lb. per sq. in. abs. and 150° F. superheat. There it expands to 35 lb. per sq. in. abs. and 0·97 dry.

Calculate:

(*a*) the change in heat value;
(*b*) the change in volume;
(*c*) the increase in speed of the steam.

Callendar's equation for superheated steam is

$$V = \frac{1 \cdot 2464}{P}(H - 835) \text{ approx.} \qquad \text{(W.S.)}$$

38. Describe briefly the changes that take place in water when it is heated in a closed vessel under constant pressure until it is converted into superheated steam.

One pound of steam at 250 lb. per sq. in. abs. and 200° F. of super heat is expanded in a nozzle to 70 lb. per sq. in. abs. and 60° F. superheat. Calculate the heat drop and the speed of the steam at the outlet from the nozzle. What is the possible power for a steam flow of 2 lb./sec. if the whole of the energy were converted into work? (W.S.)

Steam power plant, boilers and auxiliaries.

39. Give a line diagram of a complete steam plant for modern power generation, and include the more important of the auxiliary units required for the operation of the plant. Give reasons for the inclusion of such auxiliaries as you mention. (W.S.)

40. A boiler generates 7000 lb. of steam per hour at an absolute pressure of 160 lb. per sq. in. from feed water at 80° C. If the efficiency of the boiler is 75%, and the calorific value of the coal used is 8,100 C.H.U. per lb., find the number of pounds of steam generated per pound of coal consumed. The total heat of steam at 160 lb. pressure is 667·2 C.H.U. per lb. (U.L.C.I.)

41. Give a neat sketch (in two views) of either a smoke tube or a water tube boiler, with an air preheater and a superheater as part of the assembly. Show clearly :

(*a*) the position of the mountings, the pumps, and fan ;
(*b*) the water and steam circuit ;
(*c*) the air and flue gas circuit. (W.S.)

42. A boiler generates 9 lb. of dry saturated steam per lb. of fuel at an absolute pressure of 150 lb. per sq. in. from feed water at 21° C. Temperature of steam at 150 lb. pressure = 181·3° C. Sensible heat of steam at 150 lb. pressure = 183·6 C.H.U. Latent heat of steam at 150 lb. pressure = 482·9 C.H.U. If the calorific value of the fuel is 7,500 C.H.U. per lb., what fraction of the heat of combustion is actually used in generating steam? (U.L.C.I.)

43. In a boiler trial the following figures were obtained :

Water evaporated per pound of coal	8·6 lb.
Temperature of feed	92·1° C.
Temperature of steam	185·54° C.
Products of combustion per pound of coal burnt	26 lb.
Temperature of boiler house	17° C.
Temperature of gases at base of chimney	283° C.
Average specific heat of gases	0·246
Heating value of coal used	7,200 C.H.U. per lb.

Draw up a heat balance sheet for the trial in the form as shown below, assuming that the steam is dry and saturated.

Heat supplied............C.H.U.	Heat converted into steam. C.H.U. Heat carried away by gases...........C.H.U. Heat not accounted for . . ....C.H.U.

Temperature, ° C.	Sensible heat, C.H.U. per lb.	Latent heat, C.H.U. per lb.
92·1	92·05	544·00
185·54	188·07	479·50

(U.E.I.)

44. A test of a boiler having a grate area of 210 sq. ft. and a heating surface of 4,963 sq. ft. gave the following results : fuel used per hour, 4,490 lb. ; feed water used per hour, 40,360 lb. ; feed temperature, 124° C. ; absolute boiler pressure, 164 lb. per sq. in.

Determine (*a*) the ratio of heating surface to grate area. (*b*) The number of lb. of fuel burnt per sq. ft. of grate surface per hour. What is the object of determining this information? (*c*) The number of lb. of

steam generated per lb. of fuel fired, and (*d*) the equivalent evaporation from and at 100° C. per lb. of fuel fired. The temperature of steam, sensible heat of water, and the latent heat of steam at 164 lb. per sq. in. abs. are respectively 185·3° C., 187·8 C.H.U. per lb. and 479·7 C.H.U. per lb. The latent heat of steam at 100° C. is 539·3 C.H.U. (or lb. calories) per lb. (U.L.C.I.)

45. A steamer is to be supplied with boilers for engines developing 4,000 H.P. The steam is to be at 350 lb. per sq. in. abs. and 580° F. The feed supply is at 140° F., and the coal used will have a calorific value of 13,200 B.Th.U. per lb.

Calculate the total grate area, assuming the following conditions :

(*a*) That the efficiency of the boiler and superheater is 78%.

(*b*) That a firing rate of 22 lb. of coal per sq. ft. of grate area is permissible.

(*c*) The engine consumption is 13 lb. of steam per H.P. hour.

If the firing rate may be increased to 28·5 lb. per hour per sq. ft. of grate area, state the overload output of the boilers, assuming that the boiler efficiency would drop to 72 per cent. (W.S.)

46. A Lancashire boiler supplies the whole of its steam at 180 lb. per sq. in. abs., and 0·98 dry to engines developing 620 I.H.P. ; the engines consume 19·2 lb. of steam per H.P. hour, with an exhaust of 2·5 lb. per sq. in. abs. The temperature of the feed water to the boiler is 170° F. and the coal consumption is 1440 lb. per hour, of a C.V. 12,000 B.Th.U. per lb.

Calculate :

(*a*) the efficiency of the boiler ;

(*b*) the indicated thermal efficiency of the engines ;

(*c*) the overall indicated thermal efficiency of the plant. (W.S.)

47. A steam generating plant consists of economiser, boiler and superheater, with a total heating surface made up as follows : 1,550 sq. ft. in the economiser, 3,000 sq. ft. in the boiler, and 1,700 sq. ft. in the superheater. Feed water enters the economiser at 85° F. and leaves at 200° F. ; the steam leaving the boiler is at a pressure of 220 lb. per sq. in. abs. and 0·97 dry, while on leaving the superheater the steam is at 690° F. The steam generated per hour amounts to 16,000 lb.

Calculate the rate at which heat is transmitted in B.Th.U. per sq. ft. per hour in each of the three sections of the plant.

Also determine the probable fuel consumption per hour (C.V. 13,500 B.Th.U./lb.), if the efficiency of the plant is 78 per cent. (W.S.)

48. A ship of 9,000 S.H.P. when hand-fired had a coal consumption of 1·2 lb. per S.H.P. per hour when using coal with a calorific value of 13,200 B.Th.U. per lb.

The ship was then changed over to mechanical firing, when the consumption fell to 1·13 lb. per S.H.P. per hour, using the same coal.

Estimate :

(*a*) the thermal efficiency in each case ;

(*b*) the saving in fuel cost on a journey of 14 days when the fuel costs 19/- per ton ;

(*c*) the saving in bunker accommodation if one ton of coal occupied 45 cu. ft. (W.S.)

49. Write briefly on the advantages and disadvantages of using pulverised coal in (*a*) land, (*b*) marine plants.

Give a line diagram of an installation for a land boiler. (W.S.)

50. Explain the term "regenerative condenser", illustrating by sketches. Show the path of the steam and the provision for the withdrawal of air from the condenser.

Make a general lay-out sketch showing the relation of the engine or turbine, the condenser, the hotwell, and the various pumps necessary for these pieces of plant.

Indicate the information required and the calculation necessary to obtain the quantity of cooling water required by a condenser. (W.S.)

51. Make a sketch of a modern surface condenser.

In a preliminary design for a power plant the following figures were available : Steam consumption, 30,000 lb./hr. ; cooling water available in the summer months, 2,300 gallons per minute, at an average temperature of 60° F. ; temperature difference between the steam entering the condenser and the cooling water leaving the condenser required to be 10° F.

Estimate the probable vacuum obtainable, assuming that 1,000 B.Th.U. are extracted from each lb. of steam condensed.

If the cooling water supply in the winter time can be increased to 2,500 gallons per minute at an average temperature of 48° F., estimate the effect on the vacuum. (W.S.)

52. An air preheater is installed in a steam plant layout, and on test the following particulars were obtained :

Temperature of air entering heater -	60° F.
Temperature of gases entering heater -	490° F.
Temperature of gases leaving heater -	260° F.
Quantity of air entering heater - -	18·8 lb./lb. fuel.

The calorific value of the coal was 13,800 B.Th.U.

Calculate :

(*a*) Temperature of the air leaving the heater.

(*b*) Percentage of the calorific value saved.

Take specific heat of air, 0·24 ; and of gas, 0·25.

Indicate by a line sketch where such a preheater might be put in the plant layout, and state what additional plant may be required on its installation. (W.S.)

The steam prime mover, performance and testing.

53. Sketch in outline an eccentric, and describe briefly how the slide valve of a steam engine is operated. (U.L.C.I.)

54. Illustrate with sketches the meanings of the terms outside lap, inside lap, lead and angle of advance as applied to the slide valve of a steam engine.

The travel of a slide valve being 4 in., outside lap 0·75 in., and lead 0·125 in. Find the angle of advance and the crank position at admission. You may neglect the obliquity of the connecting rod. (U.E.I.)

55. With the aid of sketches describe carefully what you understand by steam lap, exhaust lap, and lead with reference to a simple slide valve.

In a simple slide valve the steam lap is 1 in., maximum opening to steam $1\frac{1}{4}$ in., lead $\frac{1}{8}$ in. Determine the angle of advance of the eccentric. (U.E.I.)

56. Make a sketch of a " D " slide valve for a steam engine showing its position, with regard to the cylinder ports, at the " Point of release ". Indicate, for this position, the direction of movement of the valve and the direction of movement of the piston.

Obtain the outside lap of such a slide valve if the travel of the valve is 5 in., the angle of advance 30°, and the lead 0·25 inch. Neglect the obliquity of the connecting rod. (U.E.I.)

57. Steam enters the cylinder of an engine at a pressure of 80 lb. per sq. in. abs. and is cut-off at 0·5 stroke. Assuming a back pressure of 17 lb. per sq. in., draw to scale a hypothetical diagram for one stroke, and find the theoretical mean effective pressure of the steam. Indicate by dotted lines how the theoretical diagram would be modified in practice. (U.L.C.I.)

58. Choose some form of turbine with which you are familiar, describe as to a beginner the working of the turbine, explaining how the energy of the steam is transferred to the blades. Does your description apply to an impulse or reaction turbine? What is the difference between these types of turbine? (U.E.I.)

59. Steam at an absolute pressure of 56 lb. per sq. in. is admitted to a cylinder of a non-condensing steam engine, and is cut-off at $\frac{3}{8}$ stroke. Draw the hypothetical indicator diagram, and indicate by dotted lines on the diagram the modifications which might be expected in an actual diagram for the same initial pressure and cut-off. Briefly explain the causes of the modifications. (U.L.C.I.)

60. Given the boiler pressure to be 135 lb. per square inch gauge, back pressure 17 lb. per square inch absolute, cut-off 0·6 stroke, expansion according to Boyle's law, draw to scale the theoretical indicator diagram for the engine. Find, in any way you please, the mean effective pressure on the piston. Denote on the diagram, using dotted lines, the

indicator diagram such as might be expected from a non-condensing steam engine fitted with a slide valve, and describe what each part of the diagram means. (U.E.I.)

61. A steam engine has a piston 9 in. in diameter and a stroke of 13 in. The engine is double-acting and makes 200 revolutions per minute. Calculate the indicated horse-power of the engine if the mid-ordinates of the indicator diagram are ·52, ·72, ·76, ·76, ·71, ·64, ·52, ·39, ·30 and ·22 in. respectively. The spring used gives a reading of 80 lb. per sq. in. to the inch. The output of the engine is measured at the same time by means of a rope brake. Calculate the mechanical efficiency of the engine if the pulls in the ends of the rope brake are 400 and 20 lb. respectively and the effective diameter of the brake wheel is 4 ft. (U.E.I.)

62. A double-acting engine has a cylinder 12 in. in diameter, 16 in. stroke. The indicator cards taken during a test have an average area of 2·78 sq. in. and an average length 3·05 in. If the indicator spring is $\frac{1}{64}$ and the speed of the shaft is 130 revs. per minute, calculate the I.H.P.

The power developed was, on test, absorbed by a rope brake fitted on the flywheel 10 feet diameter, the tensions at the two ends of the rope being 530 lb. and 54 lb. Calculate the B.H.P. and the mechanical efficiency. (W.S.)

63. From the initial steam pressure, back pressure and the point of cut-off, the mean effective pressure in a proposed engine cylinder is calculated to be 70 lb. per square inch. The calculation assumes that expansion of the steam takes place according to Boyle's Law, and that clearance and other losses are neglected. Find the dimensions of such a double-acting steam engine cylinder (bore and stroke) to develop 40 horse-power with a piston speed of 600 feet per minute, the diagram factor being 0·7 and the revolutions of the engine crank shaft 120 per minute. (U.E.I.)

64. Give a brief description, with the aid of sketches, of the construction of a steam engine indicator, and explain its use. (U.L.C.I.)

65. Give a neat sketch of the Prony type of brake and name all its parts. On a test with this type of brake the net brake load was 45 lb. acting at a radius of 3 ft.; the engine speed was 400 r.p.m.

Calculate the B.H.P. being developed.

The cooling water supply to the brake wheel was at 45° F.; the leaving temperature was 72° F., and the quantity supplied was 15½ lb. per minute.

Determine the percentage of the heat generated that was absorbed by the cooling water, and the amount dissipated to the atmosphere. (W.S.)

66. A paddle steamer is driven by a simple engine consisting of two double-acting cylinders of 30 in. diameter and 42 in. stroke. On a test the following particulars were obtained :

M.E.P. (from cards), 95 lb. per sq. in.
Steam inlet pressure, 150 lb. per sq. in. abs.
Cut-off, 0·7 stroke, r.p.m. 65.
Back pressure, 6 lb. per sq. in. abs.

Calculate : (*a*) the I.H.P. ;
(*b*) the diagram factor ;
(*c*) the maximum force on the pistons. (W.S.)

67. A single cylinder, double-acting steam engine has a cylinder of 20-inch diameter and 28-inch stroke. The steam supply is at 180 lb. per sq. in. abs. dry, the exhaust is at 4 lb. per sq. in. abs., and the engine on normal load runs at 150 r.p.m. with cut-off at half-stroke. Allowing a diagram factor of 0·88, calculate the I.H.P. developed at normal load.

Assuming the mechanical efficiency to be 85 per cent. and the actual steam consumption to be 150 per cent. of the theoretical steam consumption, determine the probable steam consumption in lb. per B.H.P. hour. (W.S.)

Internal combustion engines, performance and testing.

68. Describe, with the aid of neat sketches, one and only one of the following :

(*a*) A piston of the junk ring type with a single piston ring.
(*b*) A Bourdon pressure gauge.
(*c*) The method of governing a gas engine by the " hit and miss " method. (U.E.I.)

69. Describe, with the aid of neat sketches, one, and only one, of the following :

(*a*) A spring-loaded or a dead weight safety valve.
(*b*) A crank shaft bearing for a gas engine, provision being made for horizontal and vertical adjustment.
(*c*) The rotor of some steam turbine with which you are familiar, and state the name of the turbine. (U.E.I.)

70. State what you consider to be the most important properties of an oil fuel for an internal combustion engine.

How is the oil fuel introduced, in a suitable state for combustion, to the cylinder of an I.C. engine?

Describe and sketch the fuel supply arrangements for a Diesel or any other type of oil engine. (W.S.)

71. Describe briefly, with sketches, one method of governing gas engines ; state the advantage and disadvantage of the method described.

A single-cylinder single-acting gas engine, with a cylinder 9 in. diameter and 16 in. stroke, works at a certain load with 92 explosions per minute.

The indicator diagrams show an average M.E.P. of 88 lb. per sq. in. during working cycles.

Calculate the I.H.P. developed. (W.S.)

72. Write a brief note distinguishing between the purposes that a governor and a flywheel serve.

In the working of internal combustion engines explain briefly the function of the following:

Circulating pump; air compressor; fuel oil pump; carburettor; magneto. (W.S.)

73. In a test on a four-stroke cycle gas engine the following figures were recorded:

Diameter of cylinder - - - - -	$8\frac{1}{2}$ in.
Length of stroke - - - - - -	18 in.
Area of indicator diagram - - -	0·545 sq. in.
Length of diagram - - - - - -	1·8 in.
Scale of spring - - - - - -	$\frac{1}{300}$
Explosions per minute - - - - -	90

Calculate the indicated horse-power of the engine. If the mechanical efficiency is 0·79, what would be the brake horse-power? (U.E.I.)

74. Explain the cycle of events that occur in a gas engine working on the "Otto" cycle.

Find the indicated horse-power of a four-stroke gas engine running at 240 revolutions per minute, if the mean effective pressure during the working stroke is 70 lb. per sq. in., the diameter of the cylinder 8 in., and the stroke 15 in. Assume an explosion to be missed in every six cycles. (U.L.C.I.)

75. Sketch the form of indicator diagram you would expect to obtain from a single cylinder gas engine working on a four-stroke cycle when running under normal conditions.

In a test on a gas engine working on the four-stroke cycle the following data were obtained:

Revolutions per minute - - - -	240
Effective load on brake - - - -	63·5 lb.
Effective diameter of brake wheel -	4·56 feet
Gas consumption - - - - -	212 cub. ft. per hr.
Jacket water used - - - - -	920 lb. per hr.
Rise in temperature of jacket water	18° C.

Calculate:

(1) The brake horse-power of the engine.

(2) The gas consumption per brake horse-power per hour.

(3) The heat lost to the jacket water per hour. (U.E.I.)

76. Describe, with reference to any form of oil engine, how the fuel is introduced to the cylinder in a suitable state for combustion.

An oil engine working on the two-stroke cycle has six cylinders with a cylinder diameter of 16 in. and a stroke of 22 in. The M.E.P. during a cycle is 82 lb./sq. in. approx., when running at 300 r.p.m. The fuel

consumption amounts to 760 lb./hr., the calorific value being 19,000 B.Th.U./lb.

Calculate : (*a*) the H.P. developed ;
(*b*) the thermal efficiency. (W.S.)

77. Describe, giving sketches of the indicator diagrams obtained, the four-stroke and the two-stroke cycle Diesel engines, using air injection.

If an oil engine uses 0·39 lb. of oil per B.H.P. hour, of a calorific value 19,200 B.Th.U. per lb., determine the thermal efficiency of the engine. (W.S.)

78. Describe, with illustrations of typical indicator diagrams, the sequence of operations in the four-stroke and the two-stroke cycle Diesel engines.

An oil engine using oil of a calorific value of 19,000 B.Th.U./lb. requires 0·43 lb. of oil per B.H.P. hour. Determine the thermal efficiency of the engine. (W.S.)

79. What is meant by the terms "mechanical equivalent of heat" and "indicated thermal efficiency"?

State the heat value of the work done by an engine of 5 H.P. when it runs for one hour.

One lb. of fuel oil has a calorific value of 20,000 B.Th.U. per lb. An engine converts $\frac{3}{10}$ of the heat supplied to it by this fuel into work. Determine the amount of oil required per hour if the engine develops 10 H.P.

An oil engine develops 20 H.P. and uses 8·8 lb. of oil per hour of a calorific value 19,500 B.Th.U. per lb. What is its thermal efficiency? (W.S.)

80. A motor-car has a four-cylinder engine working on the four-stroke cycle, with cylinder diameter 3·4 in. and stroke 5 in. When travelling at 35 miles per hour the engine speed is 1,800 r.p.m. and the probable M.E.P. is 87 lb./sq. in. The petrol used has a calorific value of 19,000 B.Th.U./lb., a specific gravity of 0·80, and costs 1s. 6½d. per gallon.

Calculate :

(*a*) the I.H.P. developed ;
(*b*) the cost of fuel per mile, assuming the indicated thermal efficiency at 20 per cent. (W.S.)

81. A combined gas engine and producer plant gave, on test, the following particulars :

Producer :

Coal consumption—42 lb. per hour.
Calorific value of the coal—13,100 B.Th.U. per lb.
Gas generated—65 cub. ft. per lb. coal.
Calorific value of the gas—180 B.Th.U. per cub. ft.

Engine :

Speed—220 revs. per minute.
Explosions—82 per minute.

M.E.P.—94 lb./in.^{2}.
Jacket water—36 lb. per minute, with a temperature rise of 72° F.
Horse power developed—58 B.H.P.

The engine has cylinders of 15 in. bore and 22 in. stroke.

Draw up a heat balance for the plant, and state the overall thermal efficiency. (W.S.)

82. A Diesel oil has the following percentage composition: C, 86; H_2, 12. Determine the minimum weight of air necessary for the combustion of one pound of the oil.

On a test of a semi-Diesel engine for a motor launch using this oil an analysis showed that the air passing into the cylinders was 2½ times the theoretical quantity.

Calculate the heat being carried off by the products of combustion and by the excess air per pound of fuel, when their temperature was 920° F. The air inlet temperature was 55° F. Take the specific heat of air as 0·24 and of the products of combustion 0·25.

If the engine generated 20 I.H.P. and the fuel consumption was 8·2 lb. of oil per hour with a C.V. of 19,200 B.Th.U. per lb., draw up a simple heat balance sheet. (W.S.)

83. A marine Diesel engine, working on the single-acting four-stroke cycle, has 8 cylinders, each 22-inch diameter and 38-inch stroke. During a trial the following particulars were obtained: M.E.P., 105 lb. per sq. in.; r.p.m., 120; brake torque, 58,000 lb. ft.; fuel consumption, 9·9 lb. per minute with a calorific value of 19,500 B.Th.U. per lb.; exhaust temperature, 650° F.; air inlet temperature, 60° F.; exhaust gases per lb. of fuel, 30 lb.; specific heat of the gases, 0·25; cooling water used, 470 lb. per minute with a temperature rise of 125° F.

Calculate: (*a*) the I.H.P. developed;
(*b*) the B.H.P.;
(*c*) the brake thermal efficiency;
(*d*) a heat balance on the basis of one minute. (W.S.)

84. A rail car is driven by a Diesel engine which is coupled direct to a generator, which in turn supplies the current to motors geared to the driving axles.

The weight of the car is 35 tons. When travelling at 45 miles per hour on the level the total active resistance is 18 lb. per ton, the fuel consumption is 43 lb. per hour, and the generator output is 375 amp. at 160 volts. Taking the calorific value of the oil as 19,000 B.Th.U./lb., calculate:

(*a*) The thermal efficiency of the combined engine and generator.
(*b*) The efficiency of the combined motors and gears.
(*c*) The fuel cost per H.P. hour expended at the rail.

The oil costs 6d. per gallon and its specific gravity is 0·82. (W.S.)

85. A lorry is fitted with a four-cylinder petrol engine working on the four-stroke cycle; the cylinders are 3·2 in. diameter and 4·8 in. stroke. The top gear ratio is 5·4 and the road wheel diameter 26 in. When the

engine is running at 2,200 r.p.m. the mean effective pressure is 74 lb. per sq. in. and the fuel consumption amounts to 1·88 gallons per hour.

Calculate : (*a*) the I.H.P. ;
(*b*) the indicated thermal efficiency ;
(*c*) the road speed in miles per hour ;
(*d*) the mileage per gallon of fuel.

Take the specific gravity of the fuel as 0·77 and the C.V. as 19,500 B.Th.U. per lb. (W.S.)

ELECTROTECHNICS

The electric circuit. Electrolysis. Ohm's law.

1. State the laws of electrolysis, and describe how you would verify them experimentally.

Calculate the weight of copper which would be deposited in a refining vat in a day by a current of 2,000 amperes, if the electrochemical equivalent of the copper was 0·00033. (I.Mech.E.)

2. State Faraday's laws for determining the weight of a substance deposited in an electrolytic cell.

In a copper refinery, copper is deposited on the cathodes with a current density of 0·02 ampere per cm.^{2}. Find approximately the time needed to deposit a layer of copper on the cathode 1 cm. thick. The density of copper may be taken as 8·9 gm. per cm.^{3}, and the electrochemical equivalent = 0·000328 gm. per coulomb. If 0·3 volt is needed to send the current through the cell, find the number of kilowatt-hours needed to deposit 1 kilogram of copper. (I.E.E.)

3. Describe the general construction and give the simple theory of action of the lead accumulator.

What are the indications that an accumulator which is on charge is fully charged? (U.E.I.)

4. State Ohm's law, and show that if it is to be expressed in as simple a form as possible the units of current, electromotive force and resistance must bear a certain relation to each other. A cell sends a current of 0·06 amperes through a resistance of 24 ohms, connecting its terminals, but only 0·08 amperes through a resistance of 15 ohms. Explain this effect, and give any further details as to the cell which may be deduced from it. (I.Mech.E.)

5. The electromotive force at the terminals of a voltaic cell which is sending a current of 0·030 amperes through a wire resistance connecting the terminals is 0·96 volt. When the wire is disconnected from the terminals the electromotive force is found to be 1·10 volt. How do you explain this? (I.Mech.E.)

6. A cell of electromotive force 1·45 volts and internal resistance 3 ohms sends a current through a wire of resistance 5 ohms. How much is the electromotive force at its terminals reduced in consequence, and to what extent is the reduction permanent? (I.Mech.E.)

7. What is Ohm's law?

Two lengths of cable of resistances 0·25 and 0·35 ohms are available for transmitting 100 amperes from one point to another of an electric circuit. Calculate the electromotive forces which will be required in case (*a*) either cable is used alone, (*b*) they are connected in series, (*c*) they are connected in parallel. (I.Mech.E.)

8. An electric circuit is made up of three resistances of 2 ohms, 3 ohms, and 6 ohms respectively, joined in parallel, this group being joined in series with a group of two resistances of $4\frac{2}{3}$ ohms and 14 ohms respectively joined in parallel. The complete circuit is then connected to a cell having an e.m.f. of 1·2 volts and an internal resistance of 0·5 ohm. Find the value of the current in the cell, and in the 6-ohm and 14-ohm resistances respectively. Calculate the terminal potential difference of the cell. (U.L.C.I.)

9. On what factors does the resistance of any electrical conductor depend? A certain wireless valve requires a current of 0·1 ampere at 3·7 volts. The only electrical supply available is at 4 volts, so that a resistance is connected in series with the valve.

German silver wire is available having a diameter of 0·45 mm. If the specific resistance of this German silver is 31 microhms per cm. cube, what length of it will be required to form the necessary resistance? (U.L.C.I.)

10. An electric radiator is required to dissipate 1 kW. when connected to a 230-volt supply. If the coils of the radiator are made of wire 0·5 mm. in diameter having a specific resistance of 60 microhms per cm. cube, estimate the necessary length of wire. (I.E.E.)

11. What is meant by (*a*) the specific resistance of a conductor, (*b*) the temperature coefficient of a conductor?

The resistance of copper at 15° C. is 1·68 microhms per cm. cube. What is the resistance per inch cube at this temperature?

At a temperature of 20·5° C. the resistance of the armature of a certain continuous current generator is 0·046 ohm. After running under load the resistance becomes 0·052 ohm. If the temperature coefficient of the material is 0·004 per Cen. degree, what is the rise of temperature of the armature? (U.L.C.I.)

12. The current through a copper field coil at 15° C. was 2·0 A. when the applied pressure was 200 V. After a six-hour run the current had fallen to 1·82 A., the pressure remaining the same. Calculate the mean temperature of the coil. (Temperature coefficient of copper = ·0043.) (U.E.I.)

13. When first connected to a 100-volt circuit a cotton-covered copper coil impregnated with insulating compound carries a current of 4·0 amperes, but after several hours the current is found to have fallen to 3·0 amperes. Calculate approximately the mean temperature rise of the coil given that the temperature coefficient of copper is 0·00428 per ° C. Why is it necessary to limit the temperature rise in electrical

apparatus? Would you consider the temperature rise of the above coil a permissible one? Take the initial temperature as 15° C. (U.E.I.)

Heating effect. Electrical power.

14. Define : (*a*) Calorie, (*b*) Watt, (*c*) Joule.

A coil of wire is immersed in 145 gm. of water at 12° C. contained in a calorimeter (water equivalent 5 gm.). A constant current was passed through the coil and the following results obtained :

Current - - - - - - - -	2·15 A.
P.D. between coil terminals - - -	5·0 V.
Time the current was flowing - - -	5 min. 30 sec.
Final temperature of water - - -	17·5° C.

Assume no loss of heat and calculate the experimental value for the number of Joules, equivalent to one calorie. (U.E.I.)

15. An electric kettle is found to boil one-quarter gallon of water from 15° C. in 12 min. when taking four amperes from 220-volt mains. Calculate the efficiency of the kettle and the cost per boil if the charge for electricity is 1d. per kWh. (1 C.Th.U. = 1,400 ft. lb.) (U.E.I.)

16. What is meant by a joule of work, and what relationship exists between a joule and a foot pound of work? How many joules of work are necessary in order to produce a gram calorie of heat?

A copper kettle heated electrically contains a pint of water. Explain in detail the method you would use, the readings you would take, and the calculations you would make in order to determine (*a*) the number of foot-pounds of work which must be done by the electricity in order to boil the pint of water, (*b*) the efficiency of the kettle. (U.L.C.I.)

17. A 7 kilowatt electric water heater contains 20 gallons of water at 15° C. Assuming that 20 per cent. of the heat developed is lost, calculate the mean temperature of the water to the nearest degree C. one hour after switching on.

(1 gallon of water weighs 10 lb. ; 1 lb. = 454 gm. ; Joule's equivalent = 4·2.) (U.E.I.)

18. A small storage battery which has an average e.m.f. of 6·5 volts and a resistance of 0·02 ohm whilst charging is connected in series with a suitable resistance across 110 volt mains. The battery is charged at an average rate of 4 amperes for 15 hours. Determine (*a*) the value of the series resistance, (*b*) the cost of charging the battery at 4d. per kWh, (*c*) the percentage of the energy taken from the mains which is wasted in series resistance. (U.L.C.I.)

19. The heating coil of a hot plate intended for a 220-volt circuit has a resistance of 90 ohms when hot, and that of another for a 200-volt circuit has a resistance of 80 ohms when hot. Compare (*a*) the currents, (*b*) the heat generated in the two. (I.Mech.E.)

20. An electric immersion heater can bring a pint of water from 15° C. to boiling point in 8 minutes, the efficiency of conversion being

85 per cent. Find the resistance of the heating element for a 230-volt circuit and the cost of the operation at ½d. per unit, given that a pint of water weighs 566 gm. and that 4·2 joules is the equivalent of 1 calorie. (I.E.E.)

21. Determine the number of joules equivalent to one Board of Trade unit. If in charging an accumulator the e.m.f. increases uniformly from 2 to 2·25 volts in 12 hours at 10 amperes, and the cell discharges from 2·2 to 1·95 volts in 8 hours at 12 amperes, calculate the energy, both in watt hours and in ft. lb., put into and given out by the cell. What is the efficiency of the accumulator? (U.L.C.I.)

22. Two resistances A and B are connected in parallel and this combination is connected in series with a resistance of 84 ohms. The circuit thus formed is connected to a 100 V. supply. The current through the resistance A is 0·8 A. and that through the 84 ohm resistance is 1·0 A. Draw a connection diagram, and calculate (*a*) the value of the resistance B; (*b*) the quantity of heat developed per min. in the 84-ohm resistance. (U.E.I.)

Magnetism and electromagnetism.

23. What is a unit magnetic pole?

A unit north pole is placed on the axis of a magnet of magnetic length 12 cm. and magnetic moment 60, at a point 18 cm. from the centre of the magnet so as to have the north pole of the magnet nearer to it than the south. Find the force on the unit pole. (I.Mech.E.)

24. State the laws of action of magnetic poles on each other, and describe how you would verify them by measurement.

A north pole of strength 6 is placed on the axis of a magnet at a point 15 cm. from its centre. Find the force on the pole if the poles of the magnet are of strength 5 and its magnetic moment is 30. (I.Mech.E.)

25. Show by diagrams the nature of the magnetic field about (*a*) a long straight conductor, (*b*) a conductor bent into a circle of radius 8 cm., when the same current flows through each. Determine the relation between the fields 8 cm. from the straight conductor and at the centre of the circle. (I.Mech.E.)

26. Describe one form of electromagnet used in industry, stating what purpose it serves, and explaining on what its strength depends. (I.Mech.E.)

27. What is meant by the permeability of a sample of iron? Is the permeability of iron constant? If not, on what value does it depend?

An iron ring has a mean magnetic length of 30 cm. and a cross-section of 1·5 sq. cm. The ring is uniformly wound with 120 turns of insulated wire, and it is found that a current of 1·2 amperes through the wire produces a total magnetic flux of 12,500 lines in the ring. Determine the value of the permeability of the iron. (U.L.C.I.)

28. What is meant by the term magnetising force as applied to magnetic circuits?

A certain closed iron core has a magnetic length of 100 cm. and a cross-sectional area of 40 sq. cm. It is found that with a flux density of 5,000 lines per sq. cm. the permeability of the iron is 2,500. What is the magnetic reluctance of the core and how many ampere turns are required on the core when the flux density in the same is 5,000 lines per sq. cm.? (U.L.C.I.)

29. What is understood by magneto-motive force?

A cast steel ring has a mean diameter of 25 cm. and a cross-sectional area of 5 sq. cm. It is uniformly wound with 500 turns and has a radial air gap of 0·3 cm. Neglecting leakage and fringing, calculate the current required to establish a flux of 55,000 lines.

(Take the permeability of the steel at this flux density as 800.)

(U.E.I.)

30. A steel ring has a mean circumference of 50 cm. and a sectional area of 4 sq. cm. It is wound uniformly with 1,600 turns and has an air gap of 0·2 cm. Neglecting fringing at the air gap, calculate the current required to establish a flux of 40,000 lines. (Permeability of the steel under the above conditions = 1,000.) (U.E.I.)

31. An iron ring has a mean circumference of 45 cm. and a cross-sectional area of 5 sq. cm. It is uniformly wound with 200 turns. When the exciting current is 1 amp., the flux in the ring is 24,000 lines. Calculate: (*a*) the permeability of the iron; (*b*) the current required to establish the same flux when a radial air gap of 0·2 cm. is made in the ring. (U.E.I.)

32. Show the similarity, and also the difference, between the electric circuit and the magnetic circuit.

A solenoid 1 metre long and 2 cm. diameter is uniformly wound with one layer of covered wire, 1 millimetre diameter over the covering. How many lines of force are produced through the centre of the solenoid when the current flowing through each turn is 0·75 ampere?

If a rod of cast iron of permeability 440 is placed inside the centre of the solenoid, what is the new value of the flux density at the centre?

(U.L.C.I.)

33. How is the electromagnetic unit of current defined, and how is the practical unit derived from it? Show that the units of electromotive force have been so defined as to make the expression for the work done in a circuit in a second as simple as possible. (I.Mech.E.)

34. A specimen of iron of square section is made into a ring of internal diameter 15 cm. and external diameter 17 cm. The ring is wound uniformly with 200 turns of insulated wire, and a current of 4 amperes is passed through the coil thus formed. What is the value of the magnetic flux in the iron?

The figures below were taken from a *B-H* curve of the specimen :

H	5	10	15	20	25
B	11,000	13,500	14,700	15,300	15,900

(U.L.C.I.)

Generation of electrical power. Motors.

35. Write down the terms Force, Quantity, Power, Work as headings and then arrange the following units each under its correct heading : erg, dyne, kilowatt, horse-power-hour, foot-pound, ampere-hour, kilowatt-hour, watt, coulomb, joule.

If a dynamo is delivering power equal to 75×10^8 ergs per second, what is the value of the current flowing if the potential difference at the dynamo terminals is 120 volts? (U.L.C.I.)

36. A shunt wound dynamo is supplying 5 kW. at 50 amperes to an external circuit. The resistance of the shunt coils of the dynamo is 97 ohms, and the p.d. at the terminals is $\frac{21}{22}$ of the e.m.f. generated. Determine (*a*) the volts lost in the armature, (*b*) the resistance of the armature, (*c*) the ratio of the power used in the external circuit to total power generated. (U.L.C.I.)

37. Define the Joule, and calculate the relation between it and the foot-pound.

An effective load of 3 tons is raised vertically at a uniform speed of 22 ft. per min. Assume the overall efficiency of the motor and gearing to be 56 per cent., and calculate the input to the motor in kilowatts. (U.E.I.)

38. A motor-driven water pump delivers 18,000 gallons per hour against an effective head of 44 feet. The motor takes 37·3 A. at 200 V. Calculate (*a*) the overall efficiency and (*b*) the cost of pumping 6,000 gallons if electrical energy costs $1\frac{1}{2}$d. per B.O.T. unit. (U.E.I.)

39. Define : (*a*) gram-calorie ; (*b*) the C.G.S. unit of force ; (*c*) horse-power.

An electrically-driven pump delivers 66,000 gallons of water per hour through an effective height of 42 ft. The combined efficiency of the motor and pump is 70 per cent. and the supply pressure is 400 volts. Calculate : (*a*) the B.H.P. developed by the motor ; (*b*) the current taken by the motor. (U.E.I.)

40. State fully what is meant by a kilowatt-hour.

A certain electric motor delivers 5 B.H.P. with an efficiency of 74·6 per cent. If the motor is run from 500 volt supply, determine (*a*) the value of the current taken by the motor ; (*b*) the cost of running the motor for eight hours at 2d. per kWh. (U.L.C.I.)

41. An electric motor is required to lift a load of one ton vertically through a distance of 50 ft. in 20 sec. If the efficiency of the motor is 85 per cent. and the gearing through which it works has an efficiency of 60 per cent., calculate (*a*) the B.H.P. of the motor, and (*b*) the current which it takes from the 220-volt supply mains. (U.E.I.)

42. Prove that 1 horse-power is equal to 746 watts. (1 foot = 30·48 cm.; 1 lb. = 453·6 gm.) A tram-car weighing 8 tons requires a tractive effort of 10 lb. per ton when running at 20 miles per hour. Assuming an overall efficiency of 50%, estimate the current taken by the tram-car when running at the above speed along a level track. The p.d. applied to the motors is 550 volts. (I.E.E.)

43. What is the principle of action of a continuous current motor? What factors determine the speed at which the armature of a continuous current shunt wound motor rotates? Why does such a motor, when supplied at constant voltage, run slower if the magnetism of the field is increased? (U.L.C.I.)

44. Explain what is understood by the back e.m.f. of a motor, and give all the factors upon which its value depends. Explain clearly why the speed of a shunt motor increases when more resistance is inserted in the field circuit. (U.E.I.)

45. Explain why an e.m.f. is produced in the armature of a dynamo when rotating.

The output of a compound wound dynamo is 180 kW. at a terminal pressure of 600 volts. The resistance of the armature is 0·0042 ohm, and that of the series winding 0·0008 ohm. The shunt winding which is connected across the main terminals has a resistance of 53 ohms. Determine (*a*) the shunt field current, (*b*) the armature current, (*c*) the total power generated. (U.L.C.I.)

46. What is meant by the back e.m.f. of a motor, and on what factors does the value of this e.m.f. depend? A certain conductor on a motor armature is 30 cm. long, and it is placed at right angles to a uniform magnetic field of strength 8,000 lines per sq. cm. If the current through the conductor is 50 amperes, what is the force in lb. acting on the conductor at right angles to its axis?

(981 dynes = 1 gm.; 453·6 gm. = 1 lb.) (U.L.C.I.)

47. Determine the diameter of a copper cable required to feed a 25 B.H.P. working with an efficiency of 90% and taking current at 400 volts. The p.d. at the generator end is 410 volts, and the distance between the generator and motor is 100 yards. The specific resistance of copper may be taken as 0·7 microhms per inch cube. (U.L.C.I.)

Instruments.

48. Describe an instrument suitable for measuring an electric current of 5 amperes, and explain the principle under which it acts. (I.Mech.E.)

49. Describe the tangent galvanometer and explain why its coil must be set up in a particular plane, and how the deflection then obtained depends on the current through the instrument.

If on sending a current through the instrument no deflection were obtained, how would you determine the cause? (I.Mech.E.)

50. Describe, giving diagrams, a moving coil voltmeter suitable for comparing the electromotive forces of storage cells, and explain how its indications depend on the electromotive forces applied to it. (U.L.C.I.)

51. Explain how damping is usually obtained in moving coil instruments.

A moving coil instrument requires a current of 0·01 A. to give a full-scale deflection. Given that the resistance of the coil is 40 ohms, calculate the resistances required to make the instrument read as (*a*) a voltmeter, range 0 to 10 V., (*b*) an ammeter, 0 to 10 amp. (U.E.I.)

52. Describe, with the aid of sketches, the essential differences between moving coil and moving iron instruments and explain the mechanism by which damping is usually effected. (U.E.I.)

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ANSWERS TO EXERCISES

CHAPTER I (p. 54)

1. 59° F., 167° F., 39·2° F.; $76\frac{2}{3}$° C., 204·4° C. **2.** −459·4° F.; −$273\frac{1}{3}$° C.

3. −$43\frac{1}{3}$° C.; −25° C., $78\frac{1}{3}$° C., $65\frac{5}{9}$° C.

4. −38·2° F., 618·8° F., 1652° F., 1832° F., 2822° F., 1945·4° F., 6120° F.

5. 20° R., 50° R., $39\frac{1}{9}$° R. **6.** −40° C.

12. $8\frac{1}{8}$ in., $15\frac{5}{16}$ in., $18\frac{3}{8}$ in. **13.** 96·262 in. **14.** 1·067 ft.

15. 380·3° C. **16.** 551·72 lb. per cu. ft. **17.** 12·6 lb.; 11·97 lb.

20. 38[illegible]° C. **21.** $353\frac{1}{3}$° C. **22.** 10,920 C.H.U. per lb.

23. 3250 C.H.U. **24.** 80%. **25.** 65·95 lb.

26. 15·2 C.H.U.; 19·4%. **27.** 18·88 lb.; 218·88 lb.

28. 29·36° C. **29.** 19·28 B.Th.U. **30.** 12·75 lb. per sq. in.

31. 200 lb. per sq. in. **32.** 14·7 lb. per sq. in. **33.** 0·4904 lb. per sq. in.

37. 264·7 lb. per sq. in. **41.** 17·39 lb. **42.** 11·47 lb.

43. 5·8 lb., 11·6 lb. **44.** 7·58 lb.

45. 19·29 lb.; CO_2, 3·153 lb.; H_2O, 1·26 lb.; O, 1·024 lb.; N, 14·85 lb.

46. 14·54 lb., CO_2, 3·08 lb.; H_2O, 1·26 lb.; O, 1·672 lb.; N, 16·8 lb.

47. 2803 B.Th.U.

48. 10·66 lb., 14,180 B.Th.U. per lb.; 13,675 B.Th.U. per lb.

49. 10·38 lb.; 13,167 B.Th.U. per lb.

50. 16,914 B.Th.U. per lb.; 16,206 B.Th.U. per lb.

52. 13,373 B.Th.U. per lb. **53.** 11,291 C.H.U. per lb.

54. 7848 C.H.U. per lb.; 14,126 B.Th.U. per lb. **55.** 0·04472 lb. per cu. ft.

56. 9·5238 cu. ft. of air; no reduction.

57. 2·38 cu. ft. of air; 14·79% reduction. **59.** 500·9 B.Th.U. per cu. ft.

60. 475·7 B.Th.U.; 264·3 C.H.U. **61.** 3·46° F. **62.** 4,668,000 ft. lb.

63. 10·85%. **64.** 248 lb. **65.** 2870 lb. per hour.

66. 2·92 lb. **67.** 78·6%.

68. (*a*) 235·8; (*b*) 346·6; (*c*) 318·4; (*d*) 358·4; (*e*) 448; (*f*) 435; (*g*) 433·8; (*h*) 457·4.

70. 18·97%. **71.** 33·48%. **72.** 1,120,000 ft. lb. **73.** 8·49 min.

74. 23·2%. **75.** 8,011,000 ft. lb. **76.** $23\frac{1}{3}$ B.Th.U. per min.

77. 36·45 B.Th.U. per min. **78.** 1417 ft. lb. **79.** 7·9%.

81. 106·2 lb. **82.** 0·41. **83.** 0·0953. **84.** 30·0357 ft.

CHAPTER II (p.101)

3. 0·870 cu. ft. **4.** 36 lb. per sq. in. **5.** 6803 cu. ft.
6. 66 lb. per sq. in. **7.** 22·6 cu. ft.
9. 77·7 lb. per sq. in. abs., 311° C. abs., 690° F. abs.
10. 159° C.; 80 cu. ft. **11.** 882 lb. per sq. in. **12.** 29·85° C.
13. 27° C. **14.** 1 cu. ft. **15.** 4265° F.
16. 90·28 lb. per sq. in.; 22·69 lb. per sq. in. **17.** 10·75 cu. ft.
18. 22 cu. ft.; 329·9 lb. per sq. in.; 1·847 lb. **19.** 464 B.Th.U. per cu. ft
20. (*a*) 15·02 cu. ft. per lb. (*b*) 2·6 cu. ft. per lb. **21.** 137·7 lb.
22. 166·6° C. **23.** 0·2357 lb. **24.** 2067·5° C. **25.** 320·9 C.H.U.
26. 96·87. **27.** 41·15 ft. lb. per lb. per Cen. degree; 36·33 lb. **28.** 15·13.
29. 72,000 ft. lb. **30.** 71,280 ft. lb.
32. 66·61 lb. per sq. in.; 80 lb. per sq. in.
33. 397·7 cu. ft.; 446·3 cu. ft.; 245 cu. ft.
34. 0·1712 cu. ft.; 1·746 lb. per sq. in. **35.** 49·48 lb. per sq. in.; 701° F.
36. 10·69 cu. ft.; 432·3° C.; 4·276. **37.** 10·15 cu. ft.; 396·7° C.
39. 230·6° C.; 189·5° C.
40. 4 lb. per sq. in. abs.; 215 lb. per sq. in. abs.; 1000 lb. per sq. in. abs.
41. $h = 304{\cdot}4$ B.Th.U.; $L = 834$ B.Th.U.
43. $L = 411{\cdot}3$ C.H.U. or 740·34 B.Th.U.; 653·24 C.H.U. **44.** 12 cu. ft.
45. 422·1° F.; 1·475 cu. ft.; 1210·04.
46. 1209·4 B.Th.U.; 671·9 C.H.U.
47. (*a*) 52·16, (*b*) 482·9, (*c*) 672·08; 12,286·6 C.H.U. **48.** 1,769,800 C.H.U.
50. 1380·28 B.Th.U.; 211·48 B.Th.U. per lb.
51. 5503 C.H.U.; 86·46%. **52.** 15,501·2 B.Th.U.; 8611·8 C.H.U.
53. 194·5 lb. **54.** 1 : 1·168. **55.** 77,893 lb. per hr.
56. 0·767 cu. ft. per lb. **57.** 0·678. **58.** 743·6 C.H.U. **59.** 0·913.

CHAPTER III (p. 151)

17. 10·78%. **18.** 1153 B.Th.U. per sq. ft. per hour. **19.** 280·3° F.
20. 272·7 gal., 754 lb. **21.** 25·06 lb. **22.** 8·38%.
23. 41¾ sq. ft. **24.** 81·8%; 16·03 lb. per lb. of fuel.
25. 73·87%, 14·5 lb. per lb. of fuel; 63,800 lb. per hour. **26.** 82·75%.
27. 69·87%. **29.** 87·7%. **30.** 9·87 lb. **31.** 11·71 lb.
32. 72·95 lb., 9·4 lb. **33.** 65·42%, 9·46 lb.

34. 3735 lb. per hour. 35. 9194 lb. per hour ; 12·18 lb.
36. 86,310 lb. per hour. 37. 261,700 lb. per hour.
38. (*a*) 136·14 C.H.U. ; 2,722,800 C.H.U. ; 1396 C.H.U. per sq. ft.
39. 2327·5 B.Th.U. ; 1952 B.Th.U. ; 83·85%. 40. 76·6%.
41. 1213 lb. per hour. 42. 295° F. ; 7·58%. 43. 14·72 lb. ; 29·44%.
44. 811·4 lb. ; $\frac{5}{8}$ in. ; 1298 lb. per inch. 46. 17·41% ; 5·84%.
47. (*a*) 0·836 lb. per sq. ft. (*b*) 8·82 lb. of steam per lb. of fuel. (*c*) 77·82%. (*d*) 10·82 lb. (*e*) $51\frac{7}{16}$.
48. 15·23 lb.
49. 0·7776 in. ; 0·9721 in. ; 1·121 in. ; 1·259 in. ; 0·88 in. ; 2·12 in.
52. 23·46 lb. 53. 70·4° F. 56. 1·227 lb. per sq. in. ; 13·19 lb. per sq. in.
57. 1522 sq. ft. ; 1398 C.H.U. per sq. ft. per hour. 59. 46·3° C.
60. 231·8 cu. ft. per lb. ; 2·86 ft. 61. 1233 gal./min., 8·435 in.
62. 71·34° F. ; 28·92 in. 63. 1098 cu. ft./min.

CHAPTER IV (p. 221)

5. 1200 lb. 11. 103 B.Th.U. per lb. 12. 9·1. 13. 15·36.
14. 2432 lb., 3, 133·4 lb. per sq. in.
15. 60 lb./in.^{2} abs., 40 lb./in.^{2} abs., 30 lb./in.^{2} abs.
16. 7·69, 21·07 lb. per sq. in. 17. Crank through 54° and $81\frac{3}{4}$° ; 0·585 stroke.
18. (*a*) 1·75 in. (*b*) 3·03 in. 20. $\frac{1}{8}$ in. ; 0·765 in.
21. (*a*) $5\frac{1}{2}$ in. ; (*b*) 27°.
22. 357°, 129°, $152\frac{1}{2}$°, $332\frac{1}{2}$°, measured clockwise.
23. 357°, 129°, 164°, 322°, measured clockwise.
24. $356\frac{1}{4}$°, $128\frac{1}{2}$°, $158\frac{3}{4}$°, $325\frac{3}{4}$° ; 0·999, 0·811, 0·966, 0·915 ; $42\frac{1}{4}$°.
29. 450 lb. per inch compression. 33. 613·5.
34. 327 r.p.m., 545 ft. per min.
35. 304·5 r.p.m. if single-acting, 152·3 r.p.m. if double-acting.
36. 1280 H.P. 37. 497·3 H.P. 38. 518·2, 966·1, 2450.
40. 12·86 B.H.P. ; 17·14 I.H.P. 42. 13·71 ; 10·97 ; 80%.
43. (*a*) 37,186 B.Th.U. per min. ; (*b*) 2206 B.Th.U. per min. ; (*c*) 5·93%.
45. 12·9% ; 19,181 B.Th.U. per I.H.P. per hour.
46. (*a*) 240 r.p.m. ; (*b*) 964·2 ; (*c*) 84·37% ; (*d*) 14·78%, 17·52%.
47. 53 lb. per sq. in. 48. 44·82 lb. per sq. in.
49. (*b*) 82·98 lb. per sq. in. ; (*c*) 13·83.
50. 48·47 lb. per sq. in. ; 10,179 ft. lb.

51. 1507 lb. per hour; with expansion 21,000 ft. lb. per cu. ft.; without expansion 10,220 ft. lb. per cu. ft.

52. 11·05 in.; 16·5 in. 53. 0·7.

54. (*a*) 15·2 lb. per H.P. hour; (*b*) 408,777 B.Th.U./min.; (*c*) 50,74 B.Th.U./min.; (*d*) 14·49%; (*e*) 341,500 B.Th.U./min.; (*f*) 9·46%.

55. (*a*) 68·1%; (*b*) 8·377%.

56. (*a*) 38·8 lb./in.^{2}, 24·9 H.P.; 13·3 lb./in.^{2}, 28 H.P. (*b*) 52·9 H.P. (*c*) 43·t and 82·3%. (*d*) 27·73 lb. per B.H.P. hour. (*e*) 8·58%.

58. $S=240+14{\cdot}6P$; 502·8 lb./hour; 26·6 lb. per I.H.P. hour.

60. 182 B.Th.U. per lb.; 3020 ft./sec.; 75·33%.

63. 31·03%; 30·52%. 64. 97·6 C.H.U. per lb.; 2966 ft. per sec.; 12·4

CHAPTER V (p. 273)

31. $1{\cdot}234\times10^9$ ft. lb.; 37,390 H.P. 32. 10·14.

33. 0·568 lb. per B.H.P. hour. 34. 12·87.

35. (*a*) 69·81; (*b*) 54·45; (*c*) 39%. 36. 26·89; 74·35%.

37. 7·59; 21·32 cu. ft. per I.H.P. hour.

38. Four-stroke, 106·2 lb./in.^{2}; two-stroke, 97 lb./in.^{2}.

39. (*a*) M.E.P., 61 lb./in.^{2}; (*b*) 13·26; (*c*) 83·3%. 40. 91·27; 97·03.

41. 155·2 lb. per sq. in.; 0·566 pint/B.H.P. hour.

42. On oil, 7569 B.Th.U./B.H.P. hour; on gas, 9650 B.Th.U./B.H.P. hour.

43. (*a*) 1134 lb. ft.; (*b*) 86·9%; (*c*) 71·83 lb. per sq. in.

44. 2036 cu. ft./hour; 18·86 cu. ft./B.H.P. hour.

45. (*a*) 1663; (*b*) 67·2%; (*c*) 45·1% and 30·3%.

46. 5·72, 4·67, 81·7%, 18·35%, 22·45%, 37·3%.

47. 48·03, 35·24, 73·36%, 42·46%, 31·2%.

48.

	C.H.U. per min.		C.H.U. per min.	%
Heat supplied	2666·4	Heat to B.H.P.	830·7	31·7
		„ to mechanical losses	301·5	11·3
		„ to jacket water	698·7	26·0
		„ to exhaust and radiation by difference	836·1	31·0
TOTAL	2666·4	TOTAL	2666·4	100

49. (*a*) 36·14; (*b*) 2·41 gal. per hour; (*c*) 24·46%.

0.

	B.Th.U. per min.		B.Th.U. per min.	%
Heat supplied - -	410,800	Heat to B.H.P. - -	128,000	31·18
		,, to mechanical losses - -	23,800	5·8
		,, to jacket water -	56,130	13·62
		,, to exhaust and radiation by difference -	202,870	49·4
TOTAL	410,800	TOTAL	410,800	100

1. (*a*) 277·2 cu. ft./hour. (*b*) 7·9 cu. ft of air.

52. 13·63 lb. per lb.; 1272 B.Th.U./lb.

3. 99·28 lb. per sq. in.; 4133 B.Th.U., 3075 B.Th.U.

4.

	B.Th.U. per min.		B.Th.U. per min.	%
Heat supplied - -	454,800	Heat to I.H.P. - -	148,500	32·7
		,, to excess air -	96,430	21·1
		,, to exhaust products - -	71,750	15·75
		,, to jackets or cooling water -	138,120	30·45
TOTAL	454,800	TOTAL	454,800	100

5. (*a*) 50·87. (*b*) 41·4%. (*c*) 34·2%. (*d*) 59·12 m.p.h. (*e*) 28 miles per gallon.

56. (*a*) 390 lb. per sq. in. (*b*) 552 lb. per sq. in. (*c*) 111 lb. per sq. in. (*d*) 530·1, 388·6; 670 lb. per sq. in.

57. 90·18 lb. per sq. in.; 42%.

CHAPTER VI (p. 302)

1. 0·746. 2. 162,000 coulombs. 3. 16s. 2d. 4. 15s. 6½d.
5. 27·6. 6. 153⅓ ohms. 7. 0·275 amp. 8. 26⅔ ohms.
10. 1322·5 watts. 11. 85·3° F. 12. 1·629° C.
13. 1⅞ ohms. 14. 8¼d. 19. 1·9 amp.
27. 440 ohms; 0·523 amp. 28. 45·2 ohms; 5·09 amp.
29. 18 4/7 ohms. 30. 460 and 920 ohms.
31. 0·678 amp.; 162·2 ohms. 32. 1·77 ohms. 33. 4·58 ohms.
34. 376·4 yards. 35. 7⅛ : 1. 36. 6·92 lb. 37. 0·2 in.
38. 0·8156; 3·037; 0·6428 ohm. 39. 267·1 ohms. 40. £24 9s. 1d.

CHAPTER VII (p. 333)

4. $\frac{15}{16}$ dynes. 10. 28, −28 dynes; 4·3 cm. from the weaker pole.
11. 649·2 turns. 12. 2827 units. 13. 0·06.
14. 0·0119; 237,600 lines; 16,971 lines per sq. cm.
15. 1·087 amp.; 3148 turns; 211·5 ohms. 16. 3466 units.
26. 57·14 gauss. 27. 2·487 amp. 28. 147,000 lines. 29. 199 amp. turns.

CHAPTER VIII (p. 335)

6. 93·78%; 85·69%. 7. 73·03%. 8. 81·08%.
9. 120·3. 10. 0·4148 Cen. degree; 11·542 ohms. 11. 45° C.
12. 2126 watts; 92·32%. 13. 90·07%.
14. 137·8 amp.; $1\frac{3}{8}$ amp.; 1101 watts; 93·17%.
18. 121·2 B.H.P.; 205·5 amp. 19. 4s. $3\frac{1}{2}$d. 20. 13s.; 39·1 amp.
21. 51·4. 22. 234 volts; 95·1%; 84·9%; 89·4%. 23. 40·7.
24. 1·83 ohms; 233·7 volts. 25. 1·193 ohms; 0·6813 ohm.
26. 99 volts; 15·06 H.P.; 85·7%. 27. 104 volts.
28. 513·4 r.p.m.; 1312·5 lb.; 84·68%.

CHAPTER IX (p. 374)

7. $\frac{1}{100}$. 11. 0·5729. 13. 0·882 amp.
16. 0·0983 amp.; 14·31 ohms. 17. 4·298. 18. 2·72; 1·51 amp.; 42° 48'.
19. 2·3 amp. 20. 0·2149; 43°. 22. 12,500 ohms.

MISCELLANEOUS EXERCISES

SECTION A. HEAT AND HEAT ENGINES (p. 377)

3. 15·4° C. 4. 401·2° F., 1209·7 B.Th.U. 6. No. subtract $\frac{4}{9}$° C.
7. 608° F., 539·45 C.H.U. 8. 0·1464 in.; less.
11. 0·00001708 per Cen. degree. 12. 1·65 in. 14. 3·864 in.
15. 0·413 in. 16. 9·125 cm. 17. 0·06 cm. 19. 7160 cal.
26. 6911·5 units. 28. $59\frac{3}{7}$° C. 29. 518·4 B.Th.U. 30. 0·0961.
31. (*a*) 32° F., 212° F., 0° C., 100° C.; $\frac{5}{9}$. (*b*) 1200 B.Th.U., $666\frac{2}{3}$ C.H.U.
32. 0·41. 33. 21 C.H.U., 24·3° C. 34. 1·19d.; 108° F.
35. 1494° F. 36. 510° F. 37. 189,000 C.H.U., 378 gal. per hour.
38. $\frac{5}{9}$; 119·7 C.H.U.; 4·6 lb. 40. 80 cal. per gm. 42. 8000 cu. ft.
43. (*a*) 40 lb. per sq. in., 30 lb. per sq. in., 20 lb. per sq. in. 44. $1\frac{1}{16}$ cu. ft.

4 100 lb. per sq. in., 4 cu. ft. **46.** 135 lb. per sq. in., $1\frac{1}{27}$ cu. ft.

4. 50 lb. per sq. in., 35 lb. per sq. in. **48.** 835,100 cu. ft.

9. 250·3 c.c. **50.** (*a*) 49·5 cu. ft. (*b*) $53\frac{4}{7}$ lb.

51. 454·4 cu. ft., 426·3 cu. ft. **53.** 0·25 cu. ft., 0·2841 cu. ft.

54. 364·32 cu. ft., 341·4 cu. ft.

55. (*a*) 0·8 cu. ft. (*b*) $1\frac{1}{3}$ cu. ft. (*c*) $38\frac{1}{3}$ lb. per sq. in.

56. 656,200 C.H.U. ; 668·2 C.H.U. **57.** 2733 lb.

58. (*a*) 146·6 C.H.U. (*b*) 1086·5 C.H.U. (*c*) 11·2 lb. **59.** 680,328 C.H.U.

60. 26·3, 653·6, 591·7 ; 3685·5 C.H.U. **61.** 899 C.H.U. **62.** 5·19%.

63. 556·5 lb. **64.** 420,000 B.Th.U./hour ; 10·91%.

65 1400·4 ft. lb. per Cen. degree ; 840,240 ft. lb. **66.** 32·63%.

67. 33,000 C.H.U. ; 46·2 million ft. lb. ; $23\frac{1}{3}$ H.P. **68.** 0·102d.

8. 24·9 lb. per sq. in. **74.** 187 r.p.m. if double-acting.

5. (*a*) 4524 lb. (*b*) 5655 ft. lb. (*c*) 15·42 H.P. **76.** 8·45 H.P.

7. 59,500 C.H.U. ; 14·97% ; 28·23%.

8. (*a*) 5·76. (*b*) 1170 B.Th.U. (*c*) 20·85%. **79.** 10·01%.

0. 44·32 lb. per sq. in.

SECTION A. ELECTROTECHNICS (p. 389)

4. 5000 coulombs, 10 amp. **5.** 0·00033. **6.** 0·0009488 cm.

10. 500 ohms, 0·4 amp. **11.** 0·0656 amp. **12.** 0·9 volt.

3. (*a*) $\frac{1}{2}$ amp., (*b*) 1·8 volts, 0·9 watt.

(*a*) 10 amp. (*b*) 5 volts. (*c*) 6 amp.

5. (*a*) 1 amp. (*b*) 3·6 volts. (*c*) 14 ohms. **16.** 3 amp. **17.** 4 amp.

8. 2·6 ohms. **19.** 7 : 10. **20.** 125 ohms ; $\frac{1}{6}$th. **21.** 1 ohm.

22. 10 amp. **23.** 4·8 amp., 2s.

4 220 ohms, 0·251d., $6·674 \times 10^{-7}$ per inch cube. **25.** 0·667 microhms/in.^{2}

26. $6·972 \times 10^{-7}$ per inch cube, 2·25 kW. **27.** 0·94 mm.

28 200 cm., 6 ohms. **29.** 58,600 in., 3111 turns. **30.** 1 : 10.

31. 90,000 joules ; 0·558 lb. **32.** 50·8 ohms.

33. 27·06 ohms, 369·6 watts. **41.** $2\frac{5}{8}$. **42.** 1·066.

6·928 cm. **48.** (*a*) 9 dyne cm. (*b*) 18 dyne cm. **54.** 62·84 lines.

7. 4000 dynes. **63.** 348 kWh., 26·81. **64.** 25 amp., 7·886 H.P.

2. (*a*) $\frac{3}{160}$ ohm. (*b*) $\frac{3}{1600}$ ohm. **73.** $\frac{1}{50}$ ohm.

75. $\frac{15}{307}$ ohm, $6666\frac{2}{3}$ ohms.

SECTION B. HEAT AND HEAT ENGINES (p. 398)

1. 0·283 m. **2.** 3·03186 ft. **5.** 0·095. **6.** 14·1° C.

8. 0·318 gm.

9. (*a*) 8,100 C.H.U. (*b*) 11,340,000 ft. lb. (*c*) 5·727 H.P. hours. (*d*) 4·27 kWh.

11. 10·65%. **12.** 25·28% ; 26·25%. **13.** 0·01581° F.

14. 123 min. **15.** 8449 C.H.U./lb. ; 15,208 B.Th.U./lb.

16. 11·265 lb. air ; 13·011 lb. N_2, 1·295 lb. O_2, 3·263 lb. CO_2, 0·279 lb. H_2O.

17. 11·25 lb. air, 24·55% CO_2, 3·67% H_2O, 71·78% N_2.

18. 14·725 lb. ; 35·96%.

19. 19,487 B.Th.U./lb. ; 15·37 lb. ; 3987 B.Th.U. per lb.

20. 20,530 B.Th.U./lb. ; 34,776 lb./hour ; 36,276 lb./hour ; 454,400 cu. ft./hr.

21. 9·7 cu. ft. **22.** 1·962 cu. ft. **23.** 38·81 cu. ft./hour.

24. 642·7 cu. metres. **25.** 23 cu. ft., 6s. 8½d. **26.** 8·885 cm.

27. 89·06 lb. **28.** (*a*) : (*b*) = 0·8262 : 1.

29. 1200 ft. lb., 1077° C. ; nil, − 228° C. **33.** 655·51 C.H.U./lb.

34. (*a*) 1062·85 B.Th.U./lb. (*b*) 1125·4 B.Th.U./lb.

35. (*a*) 578 38 C.H.U./lb. (*b*) 662·5 C.H.U./lb. (*c*) 718·5 C.H.U./lb.

36. 520 C.H.U./lb., 535 C.H.U./lb.

37. 163·2 B.Th.U., 9·835 cu. ft. increase, 2860 ft./sec.

38. 107·3 B.Th.U./lb. ; 2318 ft. per sec., 303·6 H.P.

40. 10·25 lb. **42.** 77·5%.

43. all

Heat supplied -	7200 C.H.U.	Heat into steam -	4949·5 C.H.U.
		Heat to gases -	1701 C.H.U.
		Heat unaccounted -	549·5 C.H.U.
TOTAL	7200 C.H.U.	TOTAL	7200 C.H.U.

44. (*a*) 23·63. (*b*) 21·38 lb. (*c*) 8·989 lb. (*d*) 9·059 lb.

45. 274·4 sq. ft., 62,190 lb. per hour.

46. (*a*) 72·09%. (*b*) 11·19%. (*c*) 9·133%.

47. 1187 B.Th.U./sq. ft./hour, 9226 B.Th.U./sq. ft./hour, 1921 B.Th.U./sq. ft./hour, 1954 lb./hour.

48. (*a*) 16·06%, 17·06%. (*b*) £89. 15s. 6d. (*c*) 4252 cu. ft.

51. 28·48 in. summer, 29·04 in. winter.

52. (*a*) 312·3° F. (*b*) 8·249%. **54.** 25° 57′, 356° 25′ from inner dead centre.

55. 30°. 56. 1 in. 57. 50·72 lb. per sq. in. 61. 37·01, 78·18%.
62. 69·29, 58·89, 85%. 63. 7·56 in. bore, 2′ 6″ stroke.
65. 10·28, 96%, 17½ B.Th.U./min. 66. 925·8 ; 0·697 ; 106,000 lb.
67. 893·5, 35·67 lb./B.H.P./hour. 71. 20·81. 73. 21·08, 16·65.
74. 13·33. 75. 6·616 ; 32·04 cu. ft. ; 16,560 C.H.U./hour.
76. 1648·8, 29·06%. 77. 34%. 78. 31·15%.
79. 12,730 B.Th.U., 4·243 lb., 29·66%. 80. 35·9, 1·59d.

81.

	B.Th.U. per min.		B.Th.U. per min.	%
Heat supplied per min.	9170	Heat lost in producer	980	10·69
		,, to brake	2460	26·81
		,, lost in engine friction	749	8·18
		,, ,, jacket water	2592	28·25
		,, ,, exhaust, etc.	2389	26·07
Total	9170	Total	9170	100

26·81%.

82. 14·14 lb. air ; 3274 B.Th.U. per lb. ; 4402 B.Th.U. per lb.

	B.Th.U.		B.Th.U. per lb.	%
Heat supplied per lb. of fuel	19,200	Heat to I.H.P.	6207	32·5
		,, to excess air	4402	22·9
		,, to products of combustion	3274	16·9
		,, to jackets or radiation by difference	5317	27·7
Total	19,200	Total	19,200	100

83. (a) 1839. (b) 1325. (c) 29·12%.
(d)

	B.Th.U.		B.Th.U. per min.	%
Heat supplied per min.	193,050	Heat to brake	56,190	29·1
		,, to engine friction	21,810	11·3
		,, to jacket water	58,750	30·4
		,, to exhaust gases	43,807	22·7
		,, to radiation, etc.	12,493	6·5
Total	193,050	Total	193,050	100

84. (*a*) 23·56%. (*b*) 94%. (*c*) 0·668d.

85. (*a*) 31·74%. (*b*) 28·61%. (*c*) 31·52 m.p.h. (*d*) 16·76 m.p.g.

SECTION B. ELECTROTECHNICS (p. 414)

1. 57,024 gm. **2.** 376·9 hours, 0·254 kWh. **4.** 12 ohms.

6. 0·544 volt, not permanent.

7. (*a*) 25 volts, 35 volts ; 60 volts ; $14\frac{7}{12}$ volts.

8. 0·24 amp., 0·04 amp., 0·06 amp., 1·08 volt. **9.** 153·9 cm.

10. 1731 cm. **11.** 0·6615 microhms per in. cube, 35·28° C.

12. 109·9 ohms, 39·5° C. **13.** 97·9° C. **14.** 4·3.

15. 63·68%, 0·176d. **17.** 67·83° C.

18. (*a*) 0·3185 ohm. (*b*) 26·4d. (*c*) 94·09%.

19. (*a*) 1 : 1·023 ; (*b*) 1·075 : 1. **20.** 106·8 ohms, 0·033d.

21. 255 watt hours ; 676,900 ft. lb. : 199·2 watt hours ; 528,800 ft. lb.: 78·12

22. (*a*) 80 ohms. (*b*) 1200 cal. **23.** $\frac{25}{192}$ dynes. **24.** $\frac{117}{140}$ units.

25. 1 : π. **27.** μ = 1381. **28.** 159·2 ; 0·001. **29.** 6·966 amp.

30. 1·243 amp. **31.** (*a*) 859·6. (*b*) 4·8 amp.

32. 0·15, 66 lines per sq. cm. **34.** 15,300 lines. **35.** 6·25 amp.

36. (*a*) 4·762 volts. (*b*) 0·0933 ohm. (*c*) 93·54%. **37.** 5·968 kW.

38. (*a*) 40%. (*b*) 3·73d. **39.** (*a*) 20. (*b*) 37·3 amp.

40. (*a*) 10 amp. (*b*) 6s. 8d. **41.** (*a*) 16 97. (*b*) 67·7 amp.

42. 11·57 amp. **45.** (*a*) 11·32 amp. (*b*) 261·32 amp. (*c*) 157 1 kW.

46. 2·697 lb. **47.** 0·1289 in. **51.** 960 ohms, 0·04004 ohm.

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